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CAPITAL AND O&M COST RELATIONSHIPS FOR HAZARDOUS WASTE INCINERATION

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16. ABSTRACT

The objective of this study was to develop relationships between capital and operation/maintenance (O&M) costs for hazardous waste incineration and the various waste-specific, design-specific, and operational factors that affect these costs. These cost relationships have been designed so that total capital investment, annual O&M cost, and unit (dollars per lb, etc.) disposal cost estimates can be calculated for a variety of waste compositions, different incineration system designs and configurations, and a wide range of system operating conditions and performance requirements. Sequential elements of the estimation procedure are: (1) input data specifications, (2) design assumptions and engineering calculations, (3) capital cost estimation, (4) annual O&M cost estimation, and (5) unit disposal cost calculation.

The input data specifications include physical/chemical waste characteristics and throughput rates, generic incinerator design type, capacity, and operating temperature, particulate and acid gas removal requirements, energy recovery utilization, and operating schedule. When these data are specified by the user; conceptual design, material balance, energy balance, capital cost, and O&M cost calculations are performed in sequential fashion. The projected accuracy of this cost estimation procedure is ±30 to 40 percent.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs efficiently and economically.

This report provides information on capital and operation/maintenance costs for hazardous waste incineration facilities designed in accordance with RCRA performance standards. It is intended primarily for EPA utilization in assessing cost/benefit trade-offs, although it may also be useful to other individuals or organizations interested in hazardous waste incineration economics. The Incineration Research Branch, IERL-Ci, may be contacted for additional information on this subject.

David G. Stephan, Director
Industrial Environmental Research Laboratory
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ABSTRACT

The U.S. Environmental Protection Agency is currently performing a Regulatory Impact Analysis (RIA) of the RCRA performance standards for hazardous waste incineration facilities. One of the key elements of this RIA effort is the development of representative cost data for hazardous waste incineration, including (1) capital costs for new facilities designed in accordance with RCRA requirements, (2) operation and maintenance (O&M) costs for these facilities, and (3) retrofit costs for exisiting facilities to comply with RCRA standards. This report addresses capital and O&M costs. Retrofit costs are addressed in a companion report entitled, "Retrofit Cost Relationships for Hazardous Waste Incineration."

The objective of this study was to develop relationships between capital and O&M costs for hazardous waste incineration and the various waste-specific, design-specific, and operational factors that affect these costs. These cost relationships were to be designed so that total capital investment and unit (dollars per pound, etc.) O&M cost estimates could be calculated for a variety of waste compositions, different incineration system designs and configurations, and a wide range of system operating conditions and performance requirements.

Based on these objectives, a capital and O&M cost estimation model has been developed in computer-ready format. Sequential elements of the model are: (1) input data specifications, (2) design assumptions and engineering calculations, (3) capital cost estimation, (4) annual O&M cost estimation, and (5) unit disposal cost calculation. Input requirements for the model include basic physical/chemical properties of the wastes in question, plus a limited number of facility design and operating specifications. Based on these input data and numerous technical assumptions inline with current industry practice, a wide array of engineering calculations are performed to specify and design the required hardware for the facility, and to estimate the rates at which fuel, power, and other chemicals and/or utilities are consumed.

Based on the preliminary design specifications, equipment costs are estimated using a series of empirical relationships between cost and capacity, materials of construction, or other relevant design features. Estimated costs for equipment installation, indirects, and contingency are then combined with the equipment costs to determine total capital investment.

Variable costs for fuel, power, etc., are estimated from the consumption rate calculations previously mentioned and a series of regionalized unit cost data. Semivariable costs such as labor and maintenance, fixed charges to capital, and energy recovery credits (optional) are also estimated to determine the net annual O&M cost. This cost is then divided by the annual waste throughput to arrive at the final unit disposal cost estimate.

All engineering and cost calculations used in this model are consistent with standard conceptual design and budgetary pricing strategy. The projected accuracy is ±30 to 40 percent, which is suitable for the generalized purposes of the RIA and for first-cut comparisons between the costs for incineration versus other waste disposal alternatives. However, caution should be exercised when using this model for site-specific cost estimation.

This report is submitted in partial fulfillment of Contract Nos. 68-03-3043 and 68-02-3176 by Acurex Corporation, Energy & Environmental Division, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period November 1, 1981 to July 1, 1983, and work was completed as of August 1, 1983.

CONTENTS

Foreword iii
Abstract iv
Figures vii
Tables ix
Major symbols and subscript abbreviations xii
Conversion factors xvii

1. Introduction 1
    1.1 Background and objectives 1
    1.2 User guidelines 3
2. Input data specifications 7
    2.1 Overview 7
    2.2 Waste quantities and characteristics 8
    2.3 Facility characteristics 12
3. Design assumptions and engineering calculations 16
    3.1 Overview 16
    3.2 Land and site development requirements 16
    3.3 Front-end storage and handling equipment design and operation 28
    3.4 Combustion system operation 66
    3.5 Waste heat boiler operation (optional) 100
    3.6 Quench operation (optional). 109
    3.7 Scrubber system operation 112
    3.8 Fuel gas handling equipment (ID fan) operation 130
4. Capital cost estimation 133
    4.1 Overview 133
    4.2 Direct costs 135
    4.3 Indirect costs and contingency 171
    4.4 Nondepreciable costs 175
    4.5 Fixed capital and total capital investment summaries . 179
5. Annual cost estimation 180
    5.1 Overview 180
    5.2 Operating schedules and annual facility utilization . 181
    5.3 Variable costs 183
    5.4 Semivariable costs 190
    5.5 Fixed costs 195
    5.6 Energy recovery credit 196
    5.7 Annual cost summary 196
6. Unit disposal cost calculation 197

References 198

FIGURES

Number		Page
1	Overview of engineering and cost calculation procedure	5
2	Category A or B facility, 10 million Btu/hr, liquids only . . .	17
3	Category A or B facility, 10 million Btu/hr, liquids and solids	18
4	Category B facility, 50 million Btu/hr, liquids only	19
5	Category B facility, 50 million Btu/hr, liquids and solids . .	20
6	Category C facility, 50 million Btu/hr, liquids only	21
7	Category C facility, 50 million Btu/hr, liquids and solids . .	22
8	Category C facility, 100 million Btu/hr, liquids only	23
9	Category C facility, 100 million Btu/hr, liquids and solids . .	24
10	Land requirements for incineration facilities	27
11	Hypothetical drum warehouse cross section	58
12	Hypothetical drum warehouse overview	59
13	Time required for incinerator startup	96
14	Generalized flow diagram for quench/scrubber system	105
15	Breakdown of total capital investment	134
16	Site development costs (December 1982)	138
17	Installed cost of liquid waste feed pumps (December 1982) . . .	141
18	Installed cost of slurry pumps (December 1982)	142
19	Installed cost of fuel oil feed pumps (December 1982)	143
20	Installed cost of caustic soda solution pumps (December 1982)	144

FIGURES (Concluded)

Number Page

21 Air compressor (100 psig) installed cost (December 1982) . . . 151

22 Purchase cost of liquid injection incinerators (May to July 1982) 158

23 Purchase cost of waste heat boilers (July 1982) 159

24 Purchase costs for typical hazardous waste incinerator scrubbing systems receiving 1,800° to 2,200°F gas (July 1982) 161

25 Purchase cost of scrubbing systems receiving 500° to 550°F gas (July 1982) 162

26 Purchase cost of rotary kiln incinerators (May 1982) 167

27 Purchase cost of hearth incinerators (mid 1982) 170

TABLES

Number Page

1 Owner/operator scenarios 9

2 Summary of incinerator facility scenarios addressed in hypothetical site plans 25

3 Number of pumpout stations for category C facilities 30

4 Tank numbers and capacities based on facility storage requirements for a given waste type 32

5 Number and capacity of fuel oil tanks 34

6 Nominal pipe diameter versus flow 43

7 Pipe length versus incinerator capacity 44

8 Fuel oil delivery distances 46

9 Caustic soda solution delivery distances 48

10 Cart capacity versus bulk solids heat input 52

11 Cart capacity requirements 53

12 Feed hopper volume versus bulk solids heat input rate 57

13 Roller conveyor length versus drummed waste feedrate 61

14 Bulk solids storage warehouse sizes 64

15 Stoichiometric oxygen requirements for combustion 71

16 Stoichiometric yield of waste combustion products, by component 73

17 Mean heat capacities of combustion gas components between 60° and 2,000°F 75

18 Power requirements for kiln rotation 92

TABLES (Continued)

Table Page

19 Recommended startup time as a function of secondary chamber temperature 95

20 Mean heat capacities of combustion gas components between 550° and 2,000°F 102

21 Mean heat capacities of combustion gas components between 550°F and saturation temperature 104

22 Vapor pressure and heat of vaporization data for water 107

23 Mean heat capacities of combustion gas components between 2,000°F and saturation temperature 110

24 Format for presentation of particle size distribution data . . 117

25 System pressure drop versus upstream equipment configuration 132

26 Typical breakdown of site development costs 136

27 Installed costs of tanks (December 1982) 139

28 Unit installed costs for piping (December 1982) 145

29 Cost of carts for solid waste storage and transfer (December 1982) 146

30 Installed costs of bulk solid waste conveying equipment (December 1982) 148

31 Cost adjustment factors for scrubbing systems 165

32 Regional land costs (late 1982) 176

33 Unit costs for fuel oil and natural gas (January 1983) 183

34 Unit cost for electric power (January 1983) 186

35 Unit costs for water (late 1982) 186

36 Liquid nitrogen costs (mid 1982) 187

37 Unit disposal costs for landfilling (mid to late 1982) 188

38 Sewer charges (mid to late 1982) 189

TABLES (Concluded)

Table Page

39 Labor costs (mid to late 1982) 190

40 Estimated labor requirements for category A facilities 191

41 Estimated labor requirements for category B facilities 191

42 Estimated labor requirements for category C facilities 192

MAJOR SYMBOLS

Symbol	Definition	Units
A	Area	Acres, ft^2
BT	Blend tank	--
C	Cost or concentration	\$ or gr/dscf
C'	Baseline cost	\$
$\overline{Cp}$	Mean specific heat (constant pressure)	Btu/lb-°F
CAF	Cost adjustment factor	--
CSS	Caustic soda solution	--
D	Diameter	ft, in.
$\overline{D}_d$	Sauter mean droplet diameter	μm
d	Differential operator	--
DFCI	Depreciable fixed capital investment	\$
EA	Fractional excess air	--
EA'	Minimum fractional excess air	--
F	Mass flowrate	lb/hr, ton/hr
f	"Unknown factor"	--
FCI	Fixed capital investment	\$
FO	Fuel oil	--
H	Height	ft
h	Convective heat transfer coefficient	Btu/hr-ft^2-°F
HT	Holding tank	--
HV	Heating value	Btu/lb
K_{pt}	Inertial impaction parameter	--
k	Thermal conductivity coefficient	Btu-in./hr-ft^2-°F
L	Length	ft
M	Total capacity of quantity	Drums, gal, lb, yd^3
MW	Molecular weight	lb/lb-mol
N	Number	--
N_2	Nitrogen storage	--
P	Power or absolute pressure	hp or psi, in W.C.
P_t	Fractional penetration	--
$\overline{P_t}$	Overall penetration	--
p	Vapor pressure	psia
Q	Heat input or heat release rate	Btu/hr
q	Volumetric flowrate	gpm, scfh, scfm
ST	Storage tank (liquid waste)	--
T	Temperature	°F
t	Time	hr
TCI	Total capital investment	\$
U	Overall heat transfer coefficient	Btu/hr-ft^2-°F

Symbol	Definition	Units
UC	Unit cost	\$/unit consumption
UF	Annual facility utilization factor	--
V	Volume	ft^3
v	Velocity	ft/sec
W	Width	ft
X	Mass fraction	--
y	Molar or volumetric fraction	--
Δ	Change or differential	--
δ	Denotes functionality	--
λ	Latent heat of evaporation	Btu/lb
μ	Viscosity	Poise
η	Fractional efficiency	--
ρ	Density	lb/ft^3
σ	Standard deviation	--
θ	Fractional time	--

SUBSCRIPT ABBREVIATIONS

Subscripts	Reference to
Ab	Acid gas absorber
AbW	Absorber feed water
AF	Annual fixed (costs)
Adm	Administrative (costs)
Ag	Tank agitation
ASV	Annual semivariable (costs)
AV	Annual variable (costs)
AW	Ash water
add	Additional, as in air requirement
air	Combustion air
ash	Ash or ash handling
BdW	Blowdown water
BT	Blend tank
bl	Combustion air blower
bldg	Buildings in general
C	Carbon in waste/fuel
CEF	Construction expenses and fee
Cl	Chlorine in waste
CO_2	Carbon dioxide
CR	Control room
CSS	Caustic soda solution
CSS5/10/20	Caustic soda solution storage tank capacities, thousands of gallons
CW	Cold weather
calc	Calculated value
cart	Bulk solid waste carts
chem	Chemicals in general
comp	Atomizing air compressor
cont	Contingency
conv	Conveying equipment
Dep	Depreciation
DG	Dry gas
drive	Kiln rotation or charge stoker drive operations
ED	Engineering design (costs)
ER	Energy recovery (credits)
eff	Effluent
F	Fuel (costs)

Subscripts	Reference to
FH	Fixed hearth incinerator
FO	Fuel oil
FO5/10/20	Fuel oil storage tank capacities, thousands of gallons
fan	ID fan operation
feed	Waste feed operation
G	Gas
H_2	Hydrogen in water (organic)
H_2O	Free water in waste or water vapor in gas
HCl	Hydrogen chloride in gas
HT	Holding tank
heat	Tank and pipe heating
hop	Ram feeder hopper
I	Incinerator operation or exit gas
I1, I2	Primary, secondary incinerator chambers
I/T	Insurance and taxes
i	ith waste component or stream
i, i1, i2	Internal or inside, primary and secondary chambers
initial	Initial iterative value
k	kth waste component or stream
L	Labor (costs) or liquid
LI	Liquid injection incinerator
LN	Liquid nitrogen
-land	Land
M	Maintenance (costs)
max	Maximum
min	Minimum
N_2	Nitrogen in feed or gas or air
NA	Net annual (costs)
NG	Natural gas
O_2	Oxygen in feed or gas or air
O	Outside
P	Power
POS	Pumpout station
part	Particulate
p	Particle
pg	Geometric mean of the particle size distribution
pipe	Piping
pump	Pumps
Q	Quench, or quench exit gas
QD	Quench duty (thermal)
QW	Quench water
Res	Residue (disposal costs)
RK	Rotary kiln
SD	Site development (costs)
SMW	Scrubber system makeup water
ST	Liquid waste storage tanks
ST5/10/20	Storage tank capacities, thousands of gallons
s, s1, s2	Total internal surface (areas, primary and secondary chambers)

Subscripts	Reference to
sat	Saturation conditions
scrub	Total scrubber system (costs)
start	Incinerator or overall facility startup
steam	Steam generated in waste heat boilers
stoich	Stoichiometric combustion conditions
sys	Complete system
TB	Trial burn
TD	Total direct (costs)
TG	Total gas
TID	Total indirect (costs)
TIS	Total incineration system (costs)
T_{max}	Total thermal capacity
TNDC	Total nondepreciable (costs)
t	Venturi throat
tank	Tanks in general
trans	Transfer operations
UD	Unit disposal (costs)
UL	Tank truck unloading operation
Veh	Vehicles for solid waste transfer
VS	Venturi scrubber, or exit gas
VSW	Venturi scrubber feed water
W	Waste in general
WA	Waste analysis (costs)
WBS	Bulk solid waste
WC	Working capital
WCL	Combustible liquid wastes
WCS	Containerized solid wastes
Wh	Warehouse (drum storage)
WHB	Waste heat boiler
WL	Total liquid waste
WNL	Noncombustible liquid wastes
WPS	Pumpable slurry wastes
WS	Total solid wastes
WW	Wastewater (disposal costs)
water	Water (costs)

CONVERSION FACTORS

To convert from	To	Multiply by
acres	m^2	4047
Btu	kcal	0.2520
°F	°C	(°F-32)/1.8
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
gal	lit	3.785
gr	mg	64.80
hp	kw	0.7457
in.	cm	2.540
in. W.C.	kPa	0.2487
lb	kg	0.4536
psi	kPa	6.895
ton	Mg	0.9072
yd^3	m^3	0.7646

SECTION 1

INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

The U.S. Environmental Protection Agency, Office of Solid Waste, is currently conducting a Regulatory Impact Analysis (RIA) of performance standards for hazardous waste incinerators. This RIA is intended to determine both the costs and benefits of various regulatory standards. The benefits of hazardous waste incinerator regulations are being evaluated through sophisticated risk assessment studies conducted by other investigators. This study addresses the cost aspects of hazardous waste incineration; specifically, capital and operating and maintenance (O&M) costs.

Capital requirements for hazardous waste incineration facilities include front-end receiving, storage, and handling equipment for liquid or both liquid and solid wastes in various forms, the incinerator itself, flue gas and residue handling equipment, and a scrubbing system to remove particulate, acid gases, or both from the incinerator exhaust stream. If energy recovery is desired, the cost for a waste heat boiler must be added in. Additional costs are incurred for site development and, in some cases, the land itself. On top of these direct costs, it is necessary to factor in expenses for engineering, permitting, construction overhead and fee, contingencies, startup, and working capital.

During operation of the facility, costs are incurred for consumption of fuel, usually natural gas or no. 2 fuel oil; electric power; water; acid-gas neutralization chemicals such as sodium hydroxide or lime; liquid nitrogen; and the disposal of ash and/or scrubber system blowdown. Operating labor maintenance costs are also incurred, along with fixed charges to capital -- depreciation, insurance, taxes.

Each of these capital and annual operating cost elements, and their sum totals, differ from one hazardous waste incineration facility to another. Factors that affect the magnitudes of these costs include:

- Quantities and characteristics of the waste(s) burned
- Size or capacity of the facility and its various components
- Generic type of incinerator used

- Whether or not a waste heat boiler, air preheater, etc. is used for energy recovery
- Particulate loading, size distribution, and particulate removal efficiency required to meet regulatory standards
- Required removal efficiency for acid gas contaminants such as HCl
- Incinerator and air pollution control system operating conditions
- Design specifics of the incinerator and air pollution control system
- Regular operating schedule of the facility (hr/day and days/week)
- Total annual onstream time (facility utilization)

The last item on this list is, in turn, influenced by the regular operating schedule, maintenance downtime requirements, and the generation rate and/or delivery schedule of wastes to the facility. Thus, it is impossible to derive a generalized cost (dollars per pound or the equivalent) for hazardous waste disposal by incineration. The most reasonable alternative that can satisfy the requirements of the RIA is a parametric cost analysis.

Parametric evaluation of capital and O&M costs for hazardous waste incineration involves three distinct elements:

- First, the major waste- and facility-related factors affecting cost must be identified from among the numerous factors listed above. Obviously, every conceivable waste-related factor, facility design alternative, and operational alternative cannot be treated as a variable in the parametric analysis without expanding the scope of the RIA to unreasonable proportions. A careful balancing act must be performed in specifying the input variables so all factors having a major influence on cost are considered, and the scope of tne ensuing analysis is kept within reasonable limits.
- Second, functional relationships between costs and the major factors affecting these costs must be developed. These functional relationships are the tools of the parametric cost analysis.
- Finally, the cost analyses must be performed using selected, model case wastes, facility designs, and capacities representative of the industry

This study focuses on the first two elements listed above. The primary objective is to develop functional relationships for capital and O&M cost estimation; however, identification of the major factors affecting cost is essential. Actual application of the functional relationships is left to the user of this report.

1.2 USER GUIDELINES

The input data requirements, engineering calculations, and cost computation methods needed to estimate hazardous waste incineration costs are presented in sequence in Sections 2 through 6 of this report. Each of these sections is designed to be as self-explanatory and self-supporting as possible, therefore, detailed user instructions are unnecessary at this point. The following discussion focuses on general aspects of the cost development effort, including:

- An outline of the objectives of each section of this report
- Intended application of material presented herein
- Major assumptions and rationale employed
- Limitations of the information presented

Section 2, Input Data Specifications, lists data that must be provided by the user to develop capital and O&M cost estimates from the functional relationships in Sections 3 through 6. These data are largely waste oriented -- quantity, physical form, heating value, elemental composition of the organic phase, water content, ash content and composition. These are the waste characteristics that have the greatest influence on cost. A limited number of facility design and operating characteristics must also be specified, including capacity, the general type of business in which the owner/operator is involved (e.g., chemical plant versus commercial waste disposer), the generic type of incinerator employed, whether or not energy recovery equipment is used, and the emission control requirements.

Section 3 presents engineering calculations and guidelines needed to size various equipment components and/or facility subsystems, and to estimate consumption rates of fuel oil, power, water, treatment chemicals, and more minor utility requirements. The presentation is organized by cost element and/or unit operation as follows:

1. Land and site development requirements
2. Front-end storage and handling equipment design and operation
3. Combustion system operation
4. Waste heat boiler sizing
5. Quench system design and operation
6. Scrubbing system design and operation
7. Flue gas handling system operation

Section 4 presents both graphical and computational methods to estimate capital costs, based on the input data from Section 2 and the results of Section 3. Separate subsections are devoted to direct capital expenditures (e.g., for process equipment), indirect costs such as engineering and construction expenses, other nondepreciable costs such as working capital, fixed capital investment summary, and total capital investment summary. All costs are for the mid-1982 to early-1983 time frame.

Section 5 presents methods to estimate annual costs for facility operation, again based on input from Sections 2 and 3. Variable costs such as fuel and power, semivariable costs such as labor and maintenance, and fixed charges to capital (e.g., depreciation) are all addressed. In addition, methods to estimate potential energy recovery credits are presented. Again, costs are in mid-1982 to early-1983 dollars.

In Section 6, the total annual O&M costs and credits are combined with annual waste throughput estimates to derive a single net disposal cost estimate in terms of $/lb or the equivalent. This unit disposal cost is the ultimate output achieved from applying the functional relationships outlined above.

Figure 1 presents an overview of the entire engineering and cost calculation procedure. Section numbers have been included in this figure to facilitate reference to the appropriate sections.

Hazardous waste incineration capital and O&M costs calculated from this study should be used only for the previously stated purposes of the RIA or for a first-cut comparison to other waste disposal alternatives. Due to the number of simplifying and generalizing assumptions employed, the functional relationships developed in this study are not sensitive enough or powerful enough to provide accurate capital or O&M cost estimates for specific facilities.

The accuracy goal defined at the outset of this study was ±70 percent for net, unit disposal cost estimates. In all probability, accuracies associated with the functional relationships are better than this, in the ±30 to 40 percent budget estimate range. This level of accuracy should be suitable for RIA cost/benefit analyses purposes because considerably greater uncertainties than this are involved in the benefit analyses. However, ±40 percent is not considered suitable for design purposes or for site-specific cost estimation.

There are several reasons why the functional relationships cannot be made sophisticated enough for site-specific cost estimation, at least within the scope of this study. First, numerous equipment and process variations are available to the facility designer, all of which can achieve similar results for a given waste feed, but at different costs. It is impossible to consider every possible variation in developing cost relationships, therefore, common design alternatives are assumed for all cases. This is the reasonable approach to take when cost estimates for typical facilities are desired (as for purposes of the RIA), however, this approach is not acceptable for site-specific cost estimation.

Second, it was not possible for vendors to provide rigidly accurate cost estimates for the various equipment items because of the broad range of waste and facility design scenarios that needed to be addressed. Within the scope of this study, it was not feasible to reimburse equipment suppliers for the time required by their engineering staffs to prepare definitive estimates on a case-by-case basis. Most of the vendors contacted were willing,

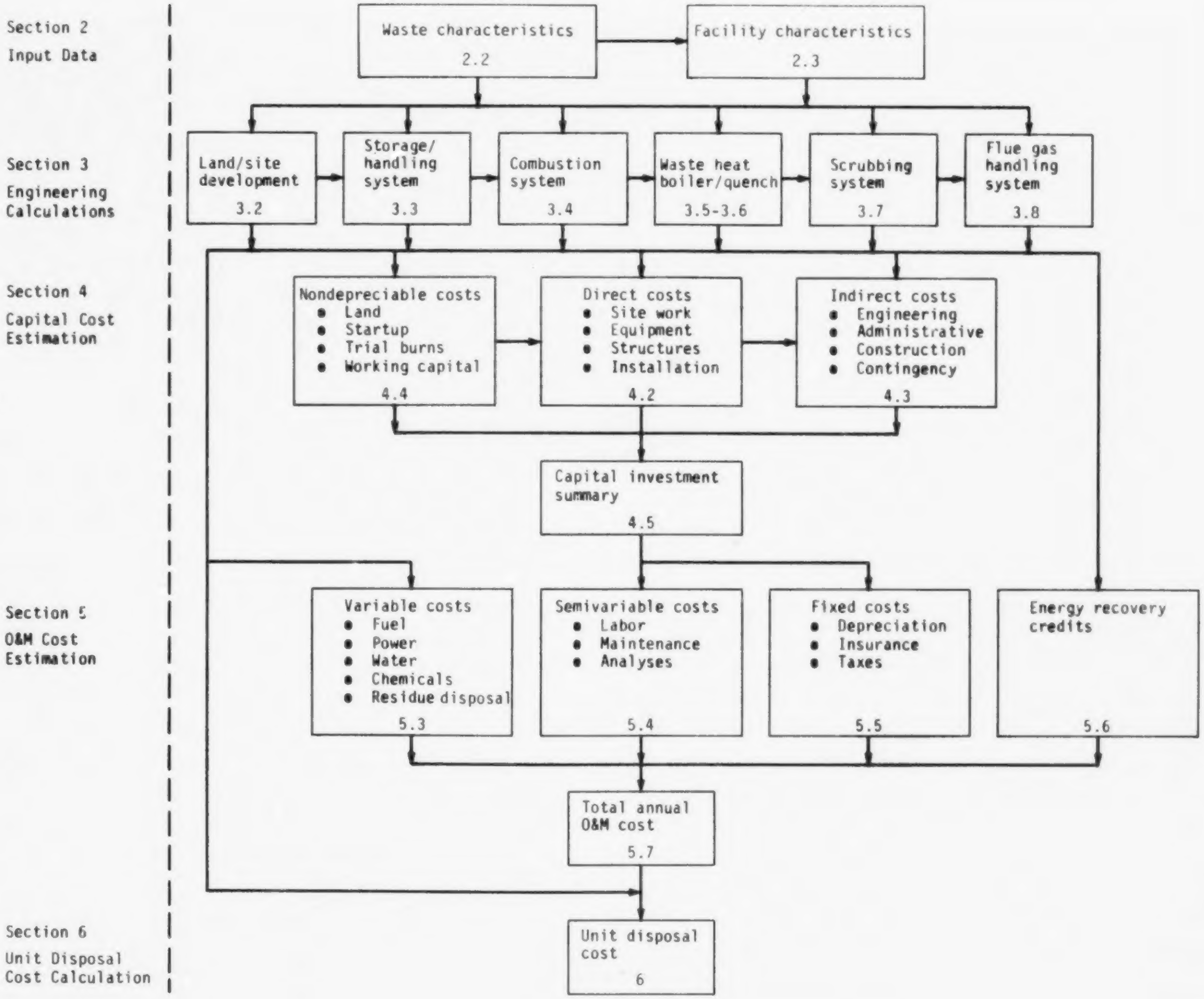

Section 2
Input Data
Section 3
Engineering Calculations
Section 4
Capital Cost Estimation
Section 5
O&M Cost Estimation
Section 6
Unit Disposal Cost Calculation
Waste characteristics 2.2
Facility characteristics 2.3
Land/site development 3.2
Storage/handling system 3.3
Combustion system 3.4
Waste heat boiler/quench 3.5-3.6
Scrubbing system 3.7
Flue gas handling system 3.8
Nondepreciable costs
● Land
● Startup
● Trial burns
● Working capital
4.4
Direct costs
● Site work
● Equipment
● Structures
● Installation
4.2
Indirect costs
● Engineering
● Administrative
● Construction
● Contingency
4.3
Capital investment summary 4.5
Variable costs
● Fuel
● Power
● Water
● Chemicals
● Residue disposal
5.3
Semivariable costs
● Labor
● Maintenance
● Analyses
5.4
Fixed costs
● Depreciation
● Insurance
● Taxes
5.5
Energy recovery credits 5.6
Total annual O&M cost 5.7
Unit disposal cost 6

Figure 1. Overview of engineering and cost calculation procedure.

however, to supply budget estimates with stated accuracies of ±20 to ±40 percent, which is suitable for the purposes of the RIA. It is recognized that this accuracy is not acceptable for site-specific cost estimation.

Third, unit costs for utilities and such are developed for a limited number of locations -- Gulf Coast area, greater Los Angeles, greater Chicago, and northern New Jersey -- areas where chemical and related industries are concentrated. While a sizable fraction of the hazardous waste incinerator population may be located in these regions in the future, other regions with different raw material and utility costs will also be represented. Thus, additional unit cost data would be needed for many site-specific evaluations. Obviously, all such possibilities could not be considered in this study.

Finally, it is extremely difficult to estimate certain costs such as maintenance even for the generalized purposes of the RIA, much less for specific facilities. Operator experience and competence play major roles in determining what the actual O&M costs will be, assuming that the original design is sound. These human factors cannot be incorporated in the functional relationship approach to cost estimation.

SECTION 2

INPUT DATA SPECIFICATIONS

2.1 OVERVIEW

To estimate realistic capital and O&M costs for hazardous waste incineration, it is necessary to specify certain information on waste quantity and composition, facility design, and operation. The feedrate, heating value, and ultimate analysis of each waste or waste blend must be known to perform the material and energy balance calculations needed for costing. It is also desirable to know if toxic, heavy metals, or alkali metals are present in the waste ash to estimate residue disposal costs and waste heat boiler applicability.

These input data are needed for any or all of five basic waste types burned in the facility -- combustible liquids,* noncombustible liquids,† pumpable slurries or sludges, bulk solids or nonpumpable sludges, and containerized wastes. This waste breakdown reflects the minimum segregation for storage and firing purposes that would be expected in most facilities.

The definition of combustible versus noncombustible liquid waste is difficult in some cases because combustor efficiency as well as waste composition influences combustibility determinations. For the purpose of this study, combustible liquids are assumed to be hydrocarbon based, usually with heating values greater than 8,000 Btu/lb. Noncombustible liquids are assumed to be either aqueous based or highly chlorinated with heating values less than 4,000 Btu/lb. Liquid wastes in the 4,000 to 8,000 Btu/lb range may fall in either category, depending on water content, incinerator temperature, excess air, and burner efficiency. For data input purposes, however, inclusion in the combustible category is recommended. This arbitrary categorization will affect storage and handling costs to a minor extent due to certain assumptions in the costing algorithms, but will not directly impact auxiliary fuel cost estimates. Auxiliary fuel requirements are estimated from heat balance calculations presented in Section 3, not from arbitrary classification of a waste as combustible or noncombustible.

---

*Capable of sustaining combustion without support fuel.

†Not capable of sustaining combustion without support fuel, although some components will in fact burn.

As indicated in Section 2.2, no allowance is made in this study for wastes containing appreciable quantities of sulfur, phosphorus, or halogens other than chlorine. This limitation is imposed for two reasons: (1) very few of the waste streams listed under RCRA as hazardous contain these species at high levels, and (2) the complexity of scrubbing and maintenance cost analyses would be increased beyond the scope of this study.

In addition to the waste input data, certain facility characteristics must be specified to estimate capital and O&M costs. Most of the facility input data listed in Section 2.3 is self-explanatory,* with the exception of Section 2.3.1, Owner/Operator Designation. Three distinct owner/operator scenarios are provided so the economic impacts of regulation can be evaluated across different segments of the hazardous waste incineration user industry. These three scenarios are:

- Institutional facilities operating small incinerators for captive waste disposal
- Industrial (primarily chemical) plants operating mid-size incinerators for captive waste disposal
- Commercial waste disposers operating large incineration facilities. Large corporate central facilities and semiprivate facilities also fall into this category

The operational aspects of these three scenarios differ in enough respects to warrant separate cost analysis. Table 1 lists various design and operating characteristics attributed to each owner/operator category. The basis for, and assumptions behind, the information presented in this table are discussed where appropriate in subsequent sections of this report.

2.2 WASTE QUANTITIES AND CHARACTERISTICS

2.2.1 Combustible Liquids

Normal feedrate, F_{WCL} = __________ lb/hr

Gross heating value, HV_{WCL} = _____ Btu/lb

Composition:

Carbon, $(X_C)_{WCL}$ = __________ lb/lb

Hydrogen, $(X_{H_2})_{WCL}$ = ________ lb/lb

Oxygen, $(X_{O_2})_{WCL}$ = __________ lb/lb

---

*Sections of the report where assumptions are made about the values which particular input data may take are given in parenthesis in Section 2.3 for user guidance.

TABLE 1. OWNER/OPERATOR SCENARIOS

	Scenario A	Scenario B	Scenario C
Owner/operator	Institution (e.g., university)	Industrial plant (e.g., chemical plant or refinery)	Commercial waste disposer, corporate central or semiprivate facility
Source of waste	100 percent onsite	100 percent onsite	100 percent offsite
Liquid injection and rotary kiln incinerator capacities	1 to 10 million Btu/hr	10 to 50 million Btu/hr	50 to 100 million Btu/hr
Hearth incinerator capacities	1 to 10 million Btu/hr	10 to 50 million Btu/hr	--
Liquid waste delivery method	Small containers from multiple onsite sources	Pumping from process(es)	Tank trucks from offsite (plus some drummed liquids)
Liquid waste storage practices	Bulk storage, single tank per waste type, minimal segregation (high Btu/low Btu)	Bulk storage, dual tanks per waste type, minimal segregation (high Btu/low Btu)	Bulk storage, dual tanks per waste type, extensive segregation for blend optimization
Liquid waste blending (other than storage)	No	No	Yes
Solid waste form as delivered, stored, and fired	Bulk or very small (5-gal) containers	Bulk or small (≤ 30 gal) containers	Bulk, small containers, or 55-gal drums
Solid-waste feed method	Semiautomatic	Semiautomatic	Automatic for bulk solids, semiautomatic for drums
Bottom ash removal method	Manual	Automatic	Automatic
Energy recovery	Optional, but improbable	Optional	Optional, but improbable
Quench/scrubber water source	Municipal supply	Onsite WWTP effluent, private well, or municipal supply	Local WWTP effluent, private well, or municipal supply
Scrubber blowdown	Municipal sewer	Onsite WWTP (central facility)	Onsite WWTP (specialized or central) or municipal sewer
Administrative/ clerical labor required	No	No	Yes
Frequent waste analyses required	No	No	Yes
Standard operating schedule	8 hr/day, 5 days/week	24 hr/day, 7 days/week	24 hr/day, 7 days/week
Total annual utilization	20 to 24 percent	50 to 90 percent	50 to 90 percent

Nitrogen, $(X_{N_2})_{WCL}$ = ________ lb/lb

Chlorine, $(X_{Cl})_{WCL}$ = ________ lb/lb

Moisture, $(X_{H_2O})_{WCL}$ = _______ lb/lb

Ash, $(X_{ash})_{WCL}$ = ____________ lb/lb

Toxic metals present in ash? Yes ____ No _____

Alkali metals present in ash? Yes ____ No _____

2.2.2 Noncombustible Liquids

Normal feedrate, F_{WNL} = __________ lb/hr

Gross heating value, HV_{WNL} = ______ Btu/lb

Composition:

Carbon, $(X_C)_{WNL}$ = ___________ lb/lb

Hydrogen, $(X_{H_2})_{WNL}$ = ________ lb/lb

Oxygen, $(X_{O_2})_{WNL}$ = __________ lb/lb

Nitrogen, $(X_{N_2})_{WNL}$ = ________ lb/lb

Chlorine, $(X_{Cl})_{WNL}$ = ________ lb/lb

Moisture, $(X_{H_2O})_{WNL}$ = _______ lb/lb

Ash, $(X_{ash})_{WNL}$ = ____________ lb/lb

Toxic metals present in ash? Yes ____ No _____

Alkali metals present in ash? Yes ____ No _____

2.2.3 Pumpable Slurries or Sludges

Normal feedrate, F_{WPS} = __________ lb/hr

Gross heating value, HV_{WPS} = ______ Btu/lb

Composition:

Carbon, $(X_C)_{WPS}$ = ___________ lb/lb

Hydrogen, $(X_{H_2})_{WPS}$ = ________ lb/lb

Oxygen, $(X_{O_2})_{WPS}$ = __________ lb/lb

Nitrogen, $(X_{N_2})_{WPS}$ = ________ lb/lb

Chlorine, $(X_{Cl})_{WPS}$ = ________ lb/lb

Moisture, $(X_{H_2O})_{WPS}$ = _______ lb/lb

Ash, $(X_{ash})_{WPS}$ = ___________ lb/lb

Toxic metals present in ash? Yes ____ No _____

Alkali metals present in ash? Yes ____ No _____

2.2.4 Bulk Solids or Nonpumpable Sludges

Normal feedrate, F_{WBS} = _________ lb/hr

Gross heating value, HV_{WBS} = _____ Btu/lb

Composition:

Carbon, $(X_C)_{WBS}$ = __________ lb/lb

Hydrogen, $(X_{H_2})_{WBS}$ = ________ lb/lb

Oxygen, $(X_{O_2})_{WBS}$ = _________ lb/lb

Nitrogen, $(X_{N_2})_{WBS}$ = ________ lb/lb

Chlorine, $(X_{Cl})_{WBS}$ = ________ lb/lb

Moisture, $(X_{H_2O})_{WBS}$ = _______ lb/lb

Ash, $(X_{ash})_{WBS}$ = ___________ lb/lb

Toxic metals present in ash? Yes ____ No _____

Alkali metals present in ash? Yes ____ No _____

2.2.5 Containerized Waste (As Fed)

Container size and construction:

5-gal fiberboard _________

30-gal fiberboard ________

55-gal steel ____________

Normal waste feedrate, F_{WCS} = _________ lb/hr

Gross heating value, HV_{WCS} = __________ Btu/lb

Composition (typical weighted average):

Carbon, $(X_C)_{WCS}$ = ____________ lb/lb

Hydrogen, $(X_{H_2})_{WCS}$ = _________ lb/lb

Oxygen, $(X_{O_2})_{WCS}$ = ___________ lb/lb

Nitrogen, $(X_{N_2})_{WCS}$ = _________ lb/lb

Chlorine, $(X_{Cl})_{WCS}$ = _________ lb/lb

Moisture, $(X_{H_2O})_{WCS}$ = ________ lb/lb

Ash, $(X_{ash})_{WCS}$ = _____________ lb/lb

Toxic metals present in ash? Yes ____ No _____

Alkali metals present in ash? Yes ____ No _____

2.3 FACILITY CHARACTERISTICS*

2.3.1 Owner/Operator Designation

A _____ B _____ C _____

2.3.2 Generic Incinerator Design Type

Liquid injection __________

Rotary kiln _______________

Multiple chamber, hearth type __________

2.3.3 Liquid Injection Incinerator Design Specifications

Total thermal capacity, Q_{Tmax} = __________ Btu/hr

Nominal operating temperature, T_{I2} = __________ °F

Minimum fractional excess air, EA' = __________ (see Section 3.4.3.4)

Severity of service:

High __________

Low __________

---

*See footnote on page 8.

If T_{I2} >1,800°F and/or chlorine or alkali metals are present in the waste, severe service may be assumed.

Time required to startup, t_{start} = __________ hr (see Section 3.4.10)

2.3.4 Rotary Kiln Incinerator Design Specifications

Total thermal capacity, Q_{Tmax} = __________ Btu/hr

Nominal kiln temperature, T_{I1} = __________ °F

Nominal afterburner temperature, T_{I2} = __________ °F

Minimum fractional excess air, EA' = __________ (see Section 3.4.4.1)

Time required for startup, t_{start} = __________ hr (see Section 3.4.10)

2.3.5 Multiple Chamber, Hearth Incinerator Design Specifications

Total thermal capacity, Q_{Tmax} = __________ Btu/hr

Nominal primary chamber temperature, T_{I1} = __________ °F

Nominal afterburner temperature, T_{I2} = __________ °F

Minimum fractional excess air, EA' = __________ (see Section 3.4.4.1)

Time required for startup, t_{start} = __________ hr (see Section 3.4.10)

Charge stoking intensity and associated particulate carryover:

High __________

Low __________

In the absence of definitive design information, a relative "high" degree of particulate carryover may be assumed for Q_{Tmax} >10 million Btu/hr (see Section 3.4.8).

2.3.6 Waste Heat Boiler Utilization and Design

Waste heat boiler utilization:

Yes __________

No __________

(see Section 3.5)

Generic waste heat boiler design:

Firetube __________

Watertube, standard service __________

Watertube, severe service __________

(see Section 4.2.3.2)

2.3.7 Particulate Control Specifications

Maximum allowable particulate loading in flue gas,

$(C_{part})_{VS}$ = __________ gr/dscf

Venturi scrubber utilization:

Yes __________

No __________

(see Section 3.7.1)

Particle size distribution data, if available:

(see Section 3.7.4 for presentation format)

Geometric mean aerodynamic particle diameter, D_{pg} = __________ μm

(see Section 3.7.4)

Geometric standard deviation of the particle size distribution,

σ_{pg} = __________ (see Section 3.7.4)

Minimum and maximum venturi pressure drop default values:

$(\Delta P_{VS})_{min}$ = __________ in. W.C.

$(\Delta P_{VS})_{max}$ = __________ in. W.C.

Initial venturi pressure drop estimate,

$(\Delta P_{VS})_{initial}$ = __________ in. W.C.

2.3.8 HCl Control Specifications

Acid gas absorber utilization:

Yes ________

No ________

Yes, if chlorine is present in the wastes.

2.3.9 Operating Schedule

Normal operating schedule:

24 hr/day, 7 days/week ________

16 hr/day, 6 days/week ________

8 hr/day, 5 days/week ________

Other (specify) ________

(see Table 1 and Section 5.2)

Fractional annual utilization, UF = ________

(see Table 1 and Section 5.2)

Number of startups per year, N_{start} = ________

(see Section 5.3.1.2)

2.3.10 Regional Considerations

Major metropolitan area:

Chicago ________

Houston ________

Los Angeles ________

Northern New Jersey ________

Average duration of subfreezing temperatures, Θ_{CW} = ________ year/year

(see Sections 3.3.2 and 3.3.3)

Average temperature over this duration, T_{CW} = ________ °F

(see Sections 3.3.2 and 3.3.3)

SECTION 3

DESIGN ASSUMPTIONS AND ENGINEERING CALCULATIONS

3.1 OVERVIEW

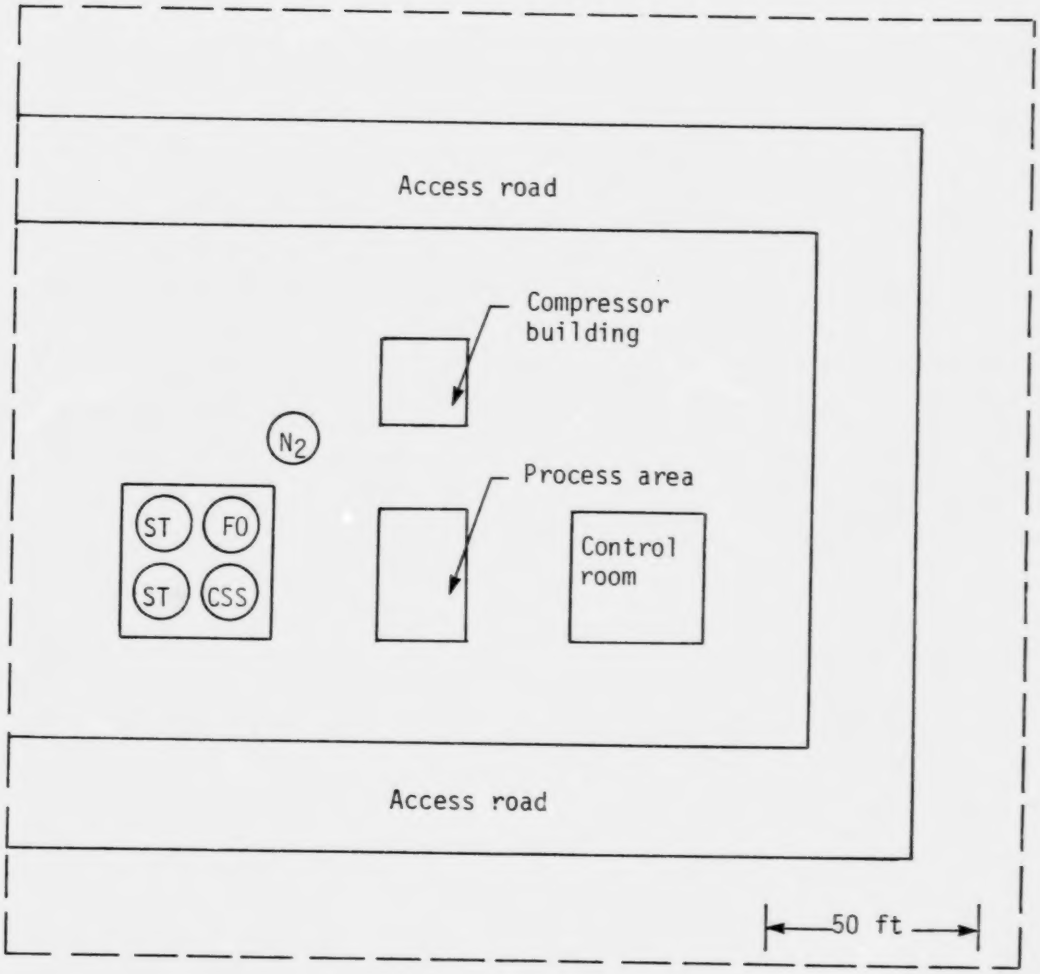
Before the input data listed in Section 2 can be used to determine capital and O&M costs, a number of engineering calculations and design assumptions must be used to size various system components and estimate raw material and utility consumption rates. Section 3.2 addresses land and site development requirements. In Section 3.3, all front-end storage and handling equipment requirements for liquid wastes, solid wastes in various forms, fuel, and chemicals are identified and sized for subsequent costing purposes. Where appropriate, raw material and utility consumption rates are also calculated, although these are usually minimal in the front-end plant. Sections 3.4 through 3.8 focus on components of the incineration system itself, namely, combustion systems, waste heat boilers, quenches, scrubbing systems, and flue gas handling equipment. Because the capacity of the incineration system is specified as an input variable in Section 2, most of the calculations in Sections 3.4 through 3.8 are material and energy balance calculations designed to estimate raw material and utility requirements for subsequent O&M cost analysis.

3.2 LAND AND SITE DEVELOPMENT REQUIREMENTS

Land and site development requirements for hazardous waste incineration facilities are estimated from the hypothetical site plans presented in Figures 2 through 9. The scenarios addressed by these site plans are summarized in Table 2.

These eight site plans cover the range of likely hazardous waste incineration facility scenarios, with one exception. Site plans for facilities with capacities less than 10 million Btu/hr are not presented because layouts and area requirements for these facilities will not be significantly different than those for the 10 million Btu/hr facilities. In this small size range, the space requirements for access roads and clearance between the various subsystems outweigh the area requirements for storage and process equipment.

These site plans will not be 100 percent representative of actual facilities. Each facility will vary in configuration, number of storage tanks required, and the amount of warehouse space necessary for solid waste storage. These differences are accounted for within the procedures for estimating the costs for storage and handling equipment. However, the site


Access road
Compressor building
N_2
Process area
ST
FO
ST
CSS
Control room
Access road
50 ft

ST = Liquid waste storage tank
FO = Fuel oil storage tank
CSS = Caustic soda solution storage tank
N_2 = Liquid nitrogen storage tank

Figure 2. Category A or B facility, 10 million Btu/hr, liquids only.

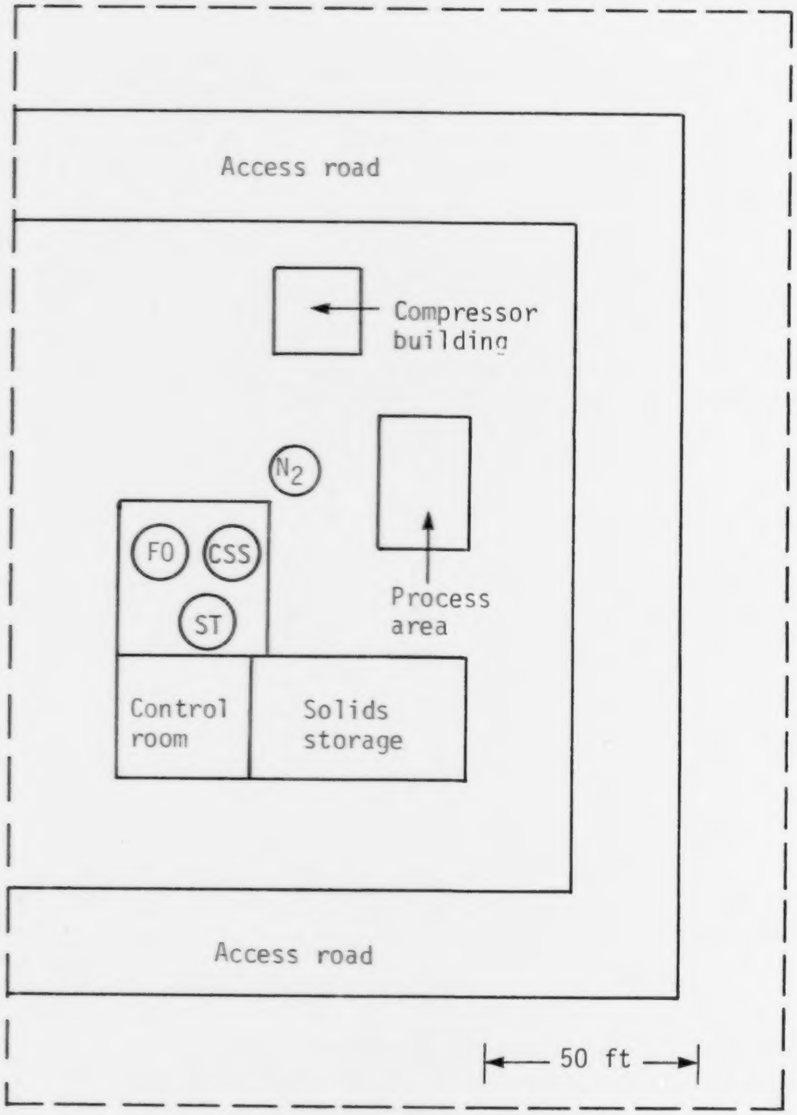

Access road
Compressor building
N2
FO
CSS
ST
Process area
Control room
Solids storage
Access road
50 ft

Figure 3. Category A or B facility, 10 million Btu/hr, liquids and solids.

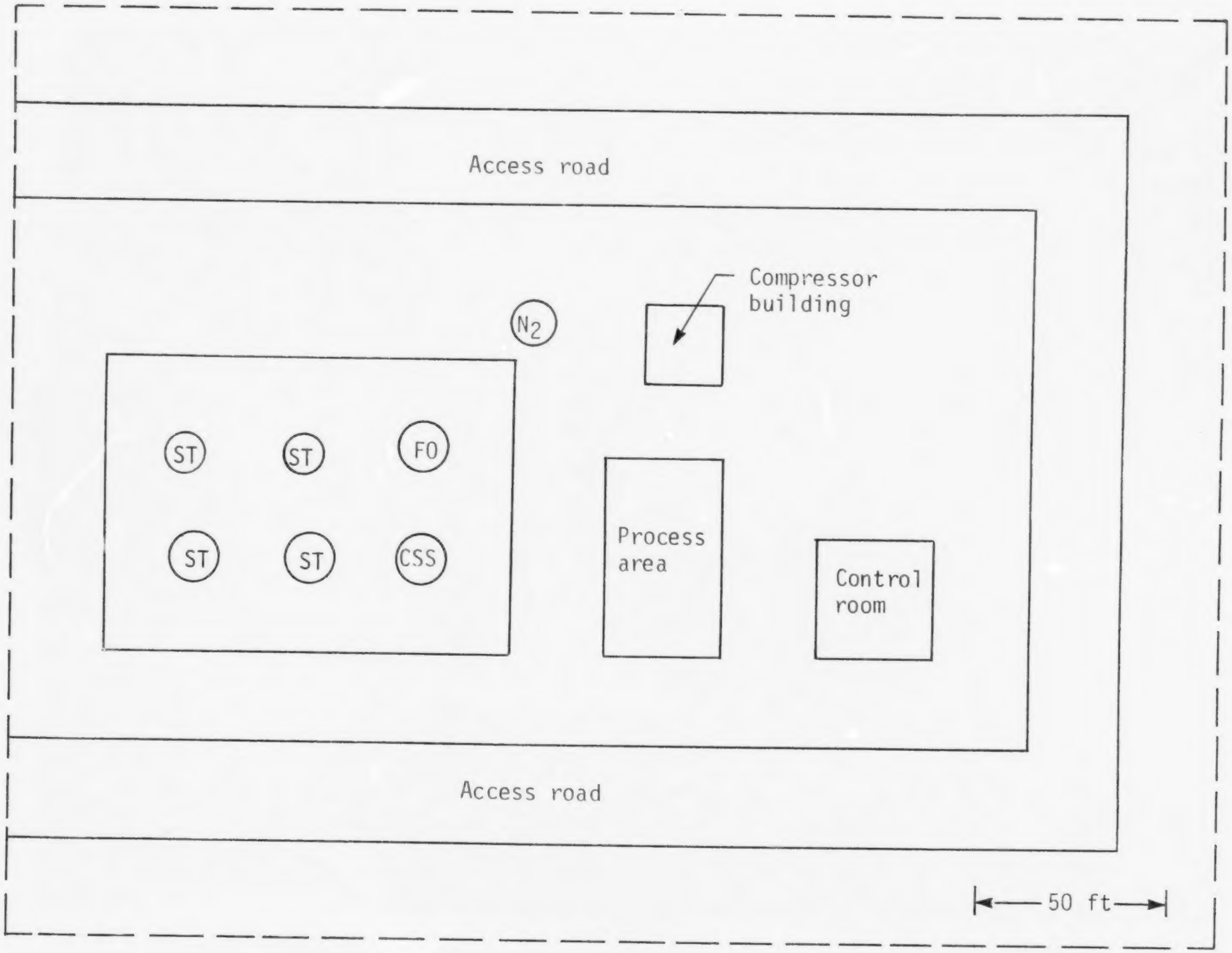

Access road
N_2
Compressor
building
ST
ST
FO
ST
ST
CSS
Process
area
Control
room
Access road
50 ft

Figure 4. Category B facility, 50 million Btu/hr, liquids only.

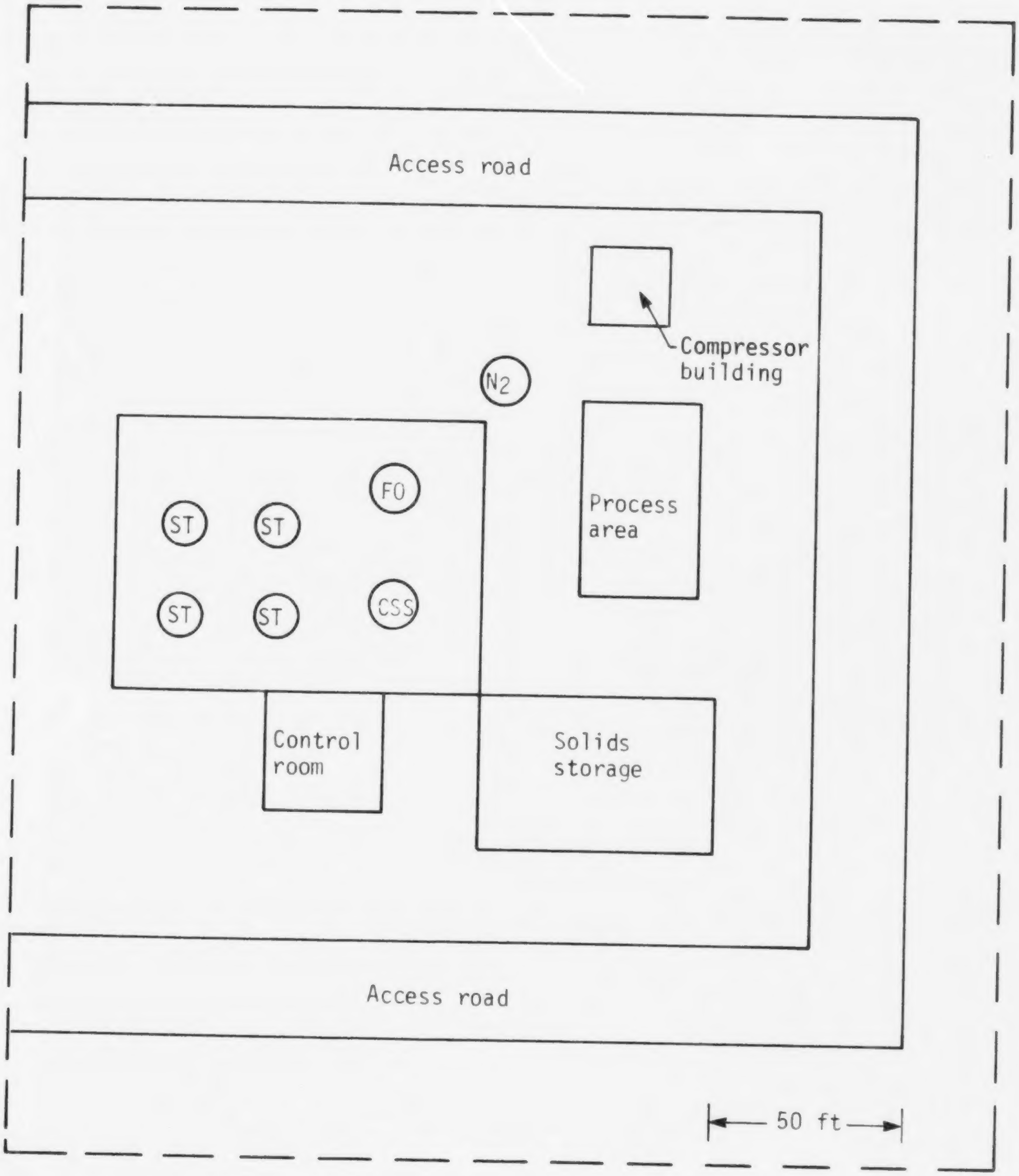
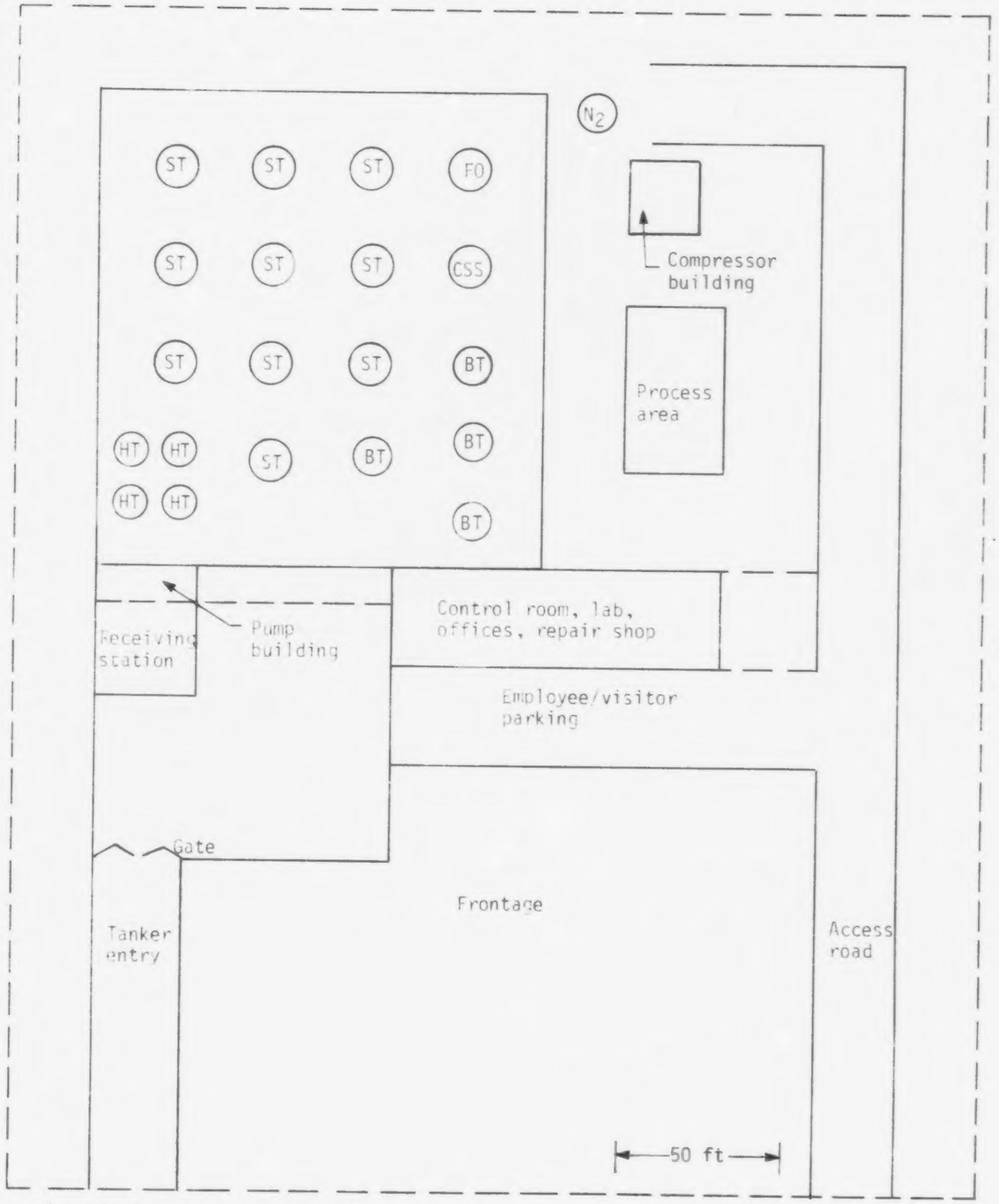

Access road
Compressor building
N2
Process area
FO
ST
ST
ST
ST
CSS
Control room
Solids storage
Access road
50 ft

Figure 5. Category B facility, 50 million Btu/hr, liquids and solids.


N2
ST
ST
ST
FO
ST
ST
ST
CSS
ST
ST
ST
BT
HT
HT
ST
BT
BT
HT
HT
BT
Compressor building
Process area
Receiving station
Pump building
Control room, lab, offices, repair shop
Employee/visitor parking
Gate
Tanker entry
Frontage
Access road
50 ft

HT = Liquid waste holding tank
BT = Liquid waste blend tank

Figure 6. Category C facility, 50 million Btu/hr, liquids only.

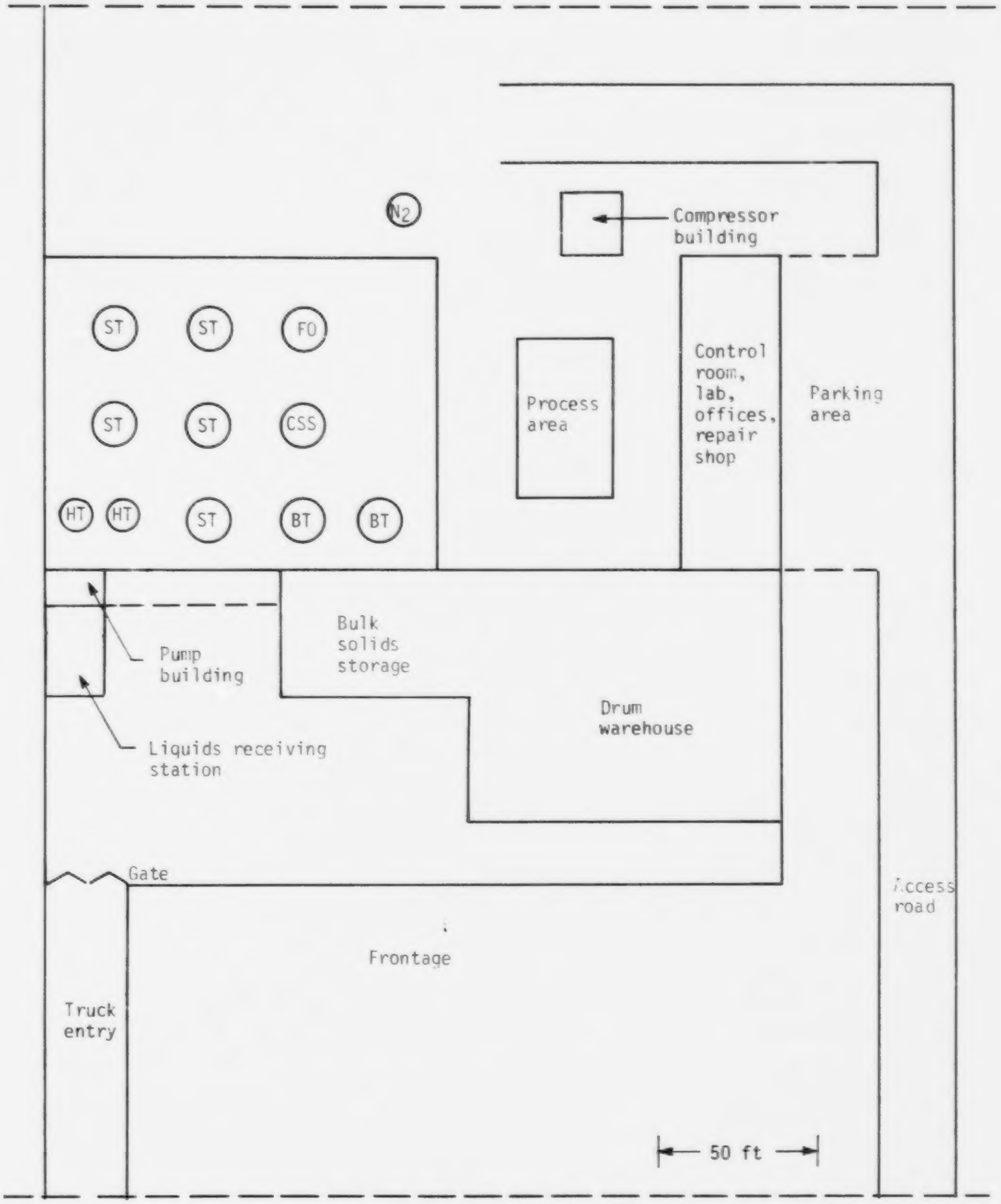

N2
Compressor building
ST
ST
FO
ST
ST
CSS
HT
HT
ST
BT
BT
Process area
Control room, lab, offices, repair shop
Parking area
Bulk solids storage
Pump building
Liquids receiving station
Drum warehouse
Gate
Access road
Frontage
Truck entry
50 ft

Figure 7. Category C facility, 50 million Btu/hr, liquids and solids.

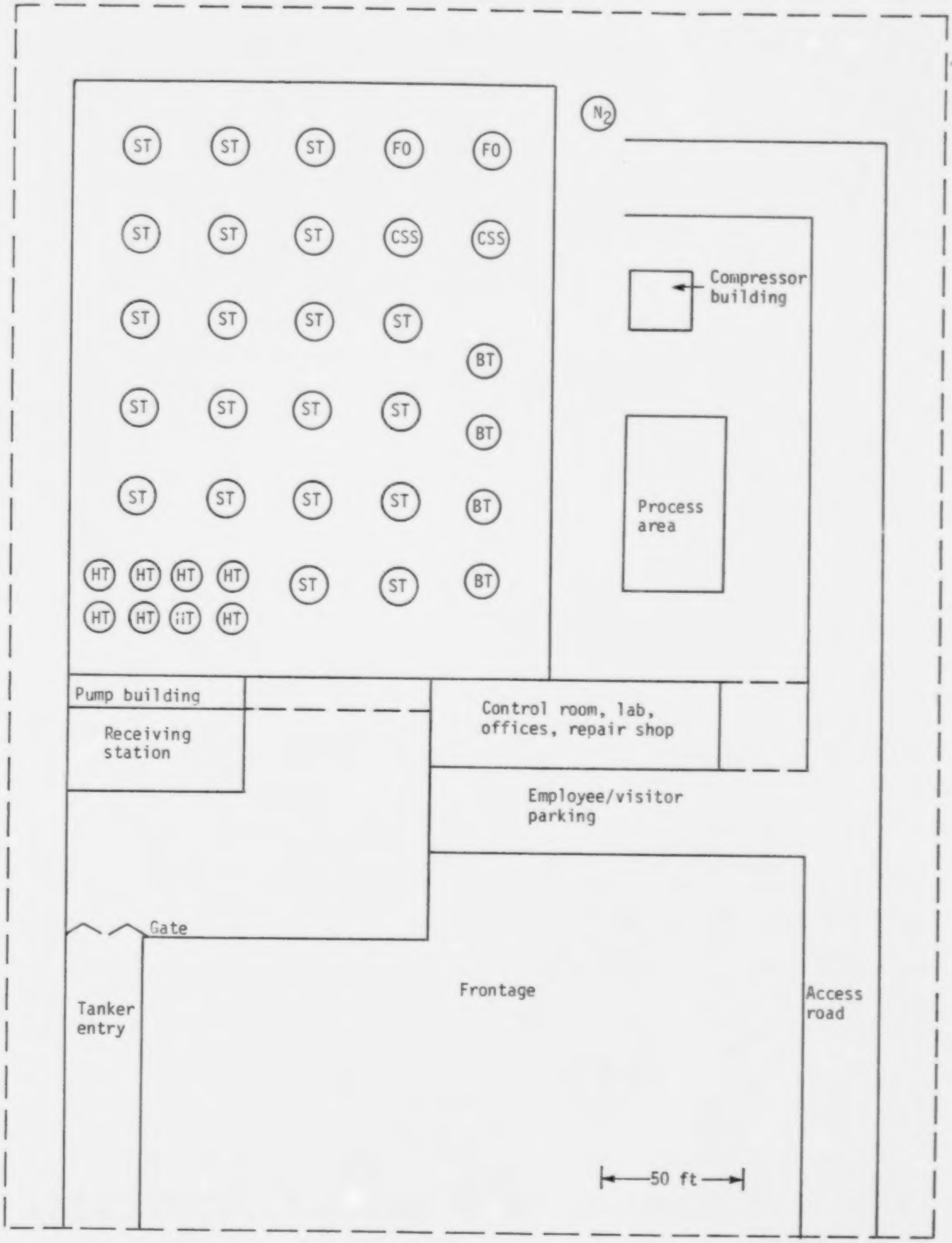

N2
ST
ST
ST
FO
FO
ST
ST
ST
CSS
CSS
Compressor building
ST
ST
ST
ST
BT
ST
ST
ST
ST
BT
ST
ST
ST
ST
BT
Process area
HT
HT
HT
HT
ST
ST
BT
HT
HT
HT
HT
Pump building
Receiving station
Control room, lab, offices, repair shop
Employee/visitor parking
Gate
Frontage
Tanker entry
Access road
50 ft

Figure 8. Category C facility, 100 million Btu/hr, liquids only.

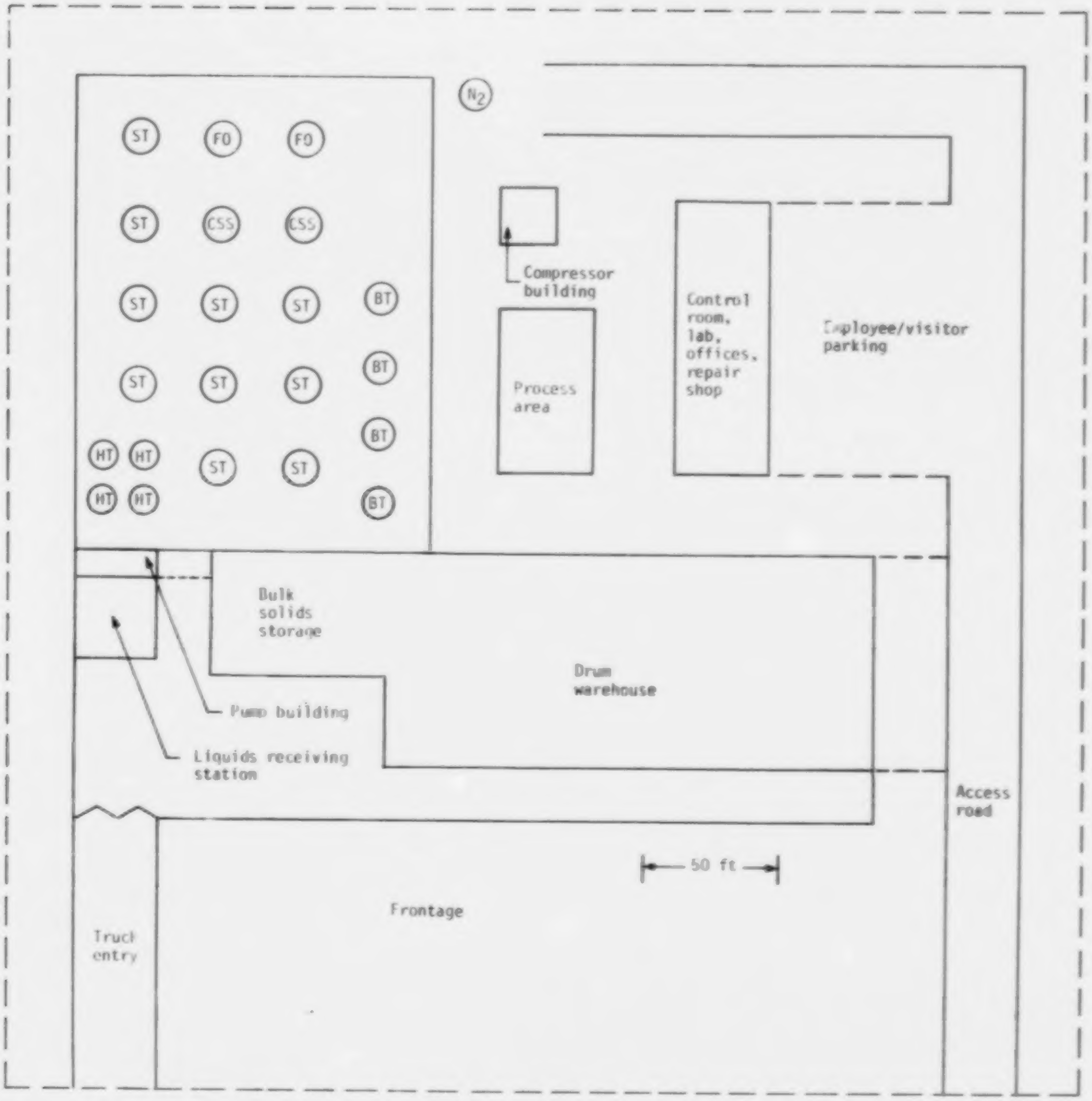

N$_2$
ST
FO
FO
ST
CSS
CSS
ST
ST
ST
BT
ST
ST
ST
BT
HT
HT
ST
ST
BT
HT
HT
BT
Compressor building
Control room, lab, offices, repair shop
Employee/visitor parking
Process area
Bulk solids storage
Drum warehouse
Pump building
Liquids receiving station
Access road
50 ft
Frontage
Truck entry

Figure 9. Category C facility, 100 million Btu/hr, liquids and solids.

TABLE 2. SUMMARY OF INCINERATOR FACILITY SCENARIOS ADDRESSED IN HYPOTHETICAL SITE PLANS

Figure	Category of facility	Thermal capacity, Q_{Tmax} (million Btu/hr)	Waste type(s)
2	A or B	10	Liquids only
3	A or B	10	Liquids, bulk solids
4	B	50	Liquids only
5	B	50	Liquids, bulk solids
6	C	50	Liquids only
7	C	50	Liquids, bulk solids, drums
8	C	100	Liquids only
9	C	100	Liquids, bulk solids, drums

plans shown in Figures 2 through 9 should provide adequate estimates of land and site development requirements for the purposes of this study.

3.2.1 Land Requirements

- Purpose and Limitations -- This section estimates space requirements as a function of facility type, capacity, and type (physical form) of waste burned, based on interpolation between the capacity extremes for a given facility type presented in Figures 2 through 9. For cost estimating purposes, the land requirement is only important for category C facilities; category A and B owner/operators are assumed to have space available for facility siting as indicated below. However, the space requirement still needs to be estimated for category A and B facilities to aid in estimating site development requirements.

- Applicability:

  -- All facilities, as a basis for determining site development needs

  -- Category C facilities only, for estimating land costs

- Assumptions:
  - -- The site plans presented in Figures 2 through 9 are reasonably representative of actual site layouts and space requirements
  - -- Category A and B owner/operators have space available on their property site for the incinerator facilities so purchase of additional land is not required
  - -- Commercial facilities (category C) require the purchase of land
- Working relationship -- Figure 10 presents approximate acreage requirements for A, B, and C facilities as a function of thermal capacity and liquid versus liquid and solid waste handling capability. From this figure, the land requirement is:

A_{land} = __________ acres

3.2.2 Site Development Requirements

- Purpose and limitations -- This section lists site development requirements for the various facility plans
- Applicability -- All facilities
- Assumptions -- Flat land with utilities available at battery limits
- Site development required:
  - -- Category A
    - Temporary facilities
    - Permits, bond, and fees
    - Survey and grade sheet
    - Clear and grub, grade, fine grade, compact
    - Access road
    - Crushed rock
    - Storm drainage
    - Storage area dike
    - Landscaping
    - Area lights
  - -- Category B -- Same as category A plus a sanitary sewer
  - -- Category C -- Same as category B plus chain-link fence

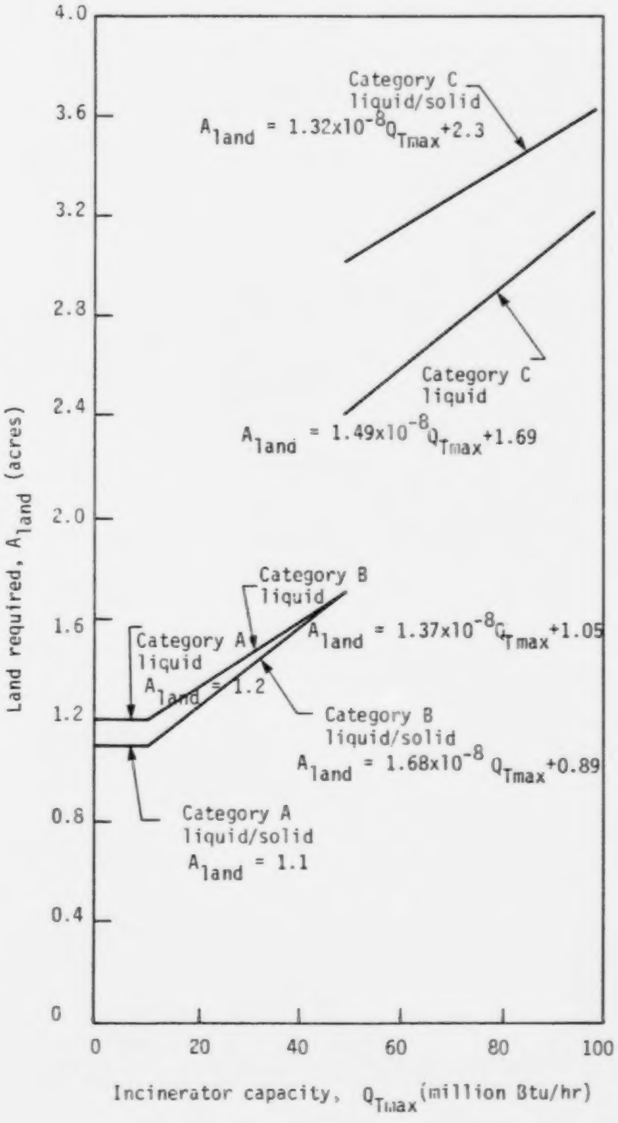


Figure 10. Land requirements for incineration facilities.

3.3 FRONT-END STORAGE AND HANDLING EQUIPMENT DESIGN AND OPERATION

Waste storage and handling practices vary widely from one hazardous waste incineration facility to another, depending on the characteristics of the waste mix, the quantities of waste handled, the nature of the process(es) generating the waste, proximity of the incineration facility to the site of waste generation, and on the preferences of the owner/operator or design engineer. Within the scope of this study, it is impossible to address every conceivable waste storage and handling scenario. Therefore, a number of generalizations and standardizing assumptions have been made to simplify the engineering and cost analyses efforts. Specifically, six different waste storage and handling scenarios are considered, based on (1) facility capacity and owner/operator designation (A, B, or C) and (2) nature of the wastes handled (liquid only or liquid and solid). These six scenarios are:

1. Category A facilities, 1 to 10 million Btu/hr, liquid waste only -- Liquid wastes arrive at the incineration facility in small containers or drums and they are pumped directly into one or more small storage tanks. Segregation is kept to a minimum for storage purposes (aqueous versus organic waste segregation). Wastes are pumped directly from storage tanks to the incinerator.

2. Category A facilities, 1 to 10 million Btu/hr, liquid and bulk solid wastes -- Bulk solid wastes arrive at the facility in carts. The carts are stored in a warehouse, then transferred to the incinerator by specially designed cart transport vehicles. Ram feeders equipped with holding hoppers are used for feeding the waste to the incinerator. No containerized wastes are handled. Liquid wastes are handled as described above.

3. Category B facilities, 10 to 50 million Btu/hr, liquid wastes only -- Liquid wastes are pumped directly from the process(es) to the storage tanks. Segregation in storage is minimal, however, dual storage tanks are generally used for each segregated waste type. Wastes are pumped directly from storage tanks to the incinerator.

4. Category B facilities, 10 to 50 million Btu/hr, liquid and bulk solid wastes -- Liquid wastes are handled as described above, and bulk solids are handled as described in scenario 2. Again, drums of waste are not fed to the incinerator.

5. Category C facilities, 50 to 100 million Btu/hr, liquid wastes only -- Liquid wastes arrive primarily by tank truck, and a receiving facility (pumpout station) is provided. Here, the wastes are pumped to small holding tanks, and then to one of many storage tanks. Considerable segregation is employed with at least two storage tanks per waste type. From storage, wastes are pumped to one of several blend tanks (batch tanks), which feed the incinerator.

6. Category C facilities, 50 to 100 million Btu/hr, liquid and solid wastes -- Bulk solid wastes arrive by truck and are stored in a recessed bunker within a warehouse. An underdrag screw conveyor-bucket elevator-covered belt conveyor system automatically transfers the waste from storage to the ram feeder hopper, from which it is charged at preset intervals to the incinerator. Drummed wastes also arrive by truck and are transferred on pallets by a lift truck to an appropriate location in the drum storage warehouse. When needed, the drums are loaded onto a semiautomatic indexing roller conveyor system which transfers them to a drum elevator near the process area. From the top of the drum elevator, drums proceed by roller conveyor through dual air locks into the kiln feed chute. Liquid wastes are handled as described in scenario 5.

In the following sections, engineering calculations and guidelines are provided to estimate the number, size, and operating requirements (if any) for the various pieces of equipment mentioned above. To minimize repetitious calculations, these sections are organized by type of equipment rather than by the facility walk-through approach. However, it is clearly indicated when the particular equipment component is needed for a given type of facility.

3.3.1 Tanks

In all incineration facilities, tanks are required to perform one function or another. These functions include liquid waste storage, holding, and blending, fuel oil storage, caustic soda solution storage, and liquid nitrogen storage. Some common features and differences between these tanks (assumed for the purposes of this study) are as follows:

- All tanks are above ground, conical fixed roof, top fill/bottom discharge design supported by concrete pads
- Liquid waste tanks are carbon steel construction, well insulated and equipped for nitrogen blanketing, with low-speed top-supported agitators and suction line or recirculatory heaters. Nominal capacities are 5,000, 10,000, and 20,000 gal.
- No. 2 fuel oil tanks are similar to liquid waste tanks except that no agitation or heating is provided
- Caustic storage tanks are not nitrogen blanketed
- Liquid nitrogen tanks are rented from the nitrogen supplier, so they are not considered part of the capital facility

3.3.1.1 Liquid Waste Holding Tanks

- Purpose and limitations -- This section provides guidelines to determine the number and capacity of holding tanks required in category C facilities

- Applicability -- All category C facilities
- Assumptions:
  - Holding tanks are used only in category C facilities as an intermediary between tank truck unloading and storage
  - All holding tanks have a 5,000-gal capacity, the equivalent of a full tank truck load
  - Two holding tanks are provided for each pumpout station, one for organic wastes and one for high aqueous wastes
  - The relationship between number of pumpout stations, waste mix, and capacity is shown in Table 3.
- Working relationship -- Based on these assumptions, the number of holding tanks (N_{HT}) is given by:

$$N_{HT} = 2\ N_{POS} = \_\_\_\_\_\_\_\_\_\_\_\_$$

3.3.1.2 Liquid Waste Storage Tanks

- Purpose and limitations -- This section provides guidelines to estimate the number and capacity of storage tanks required for combustible liquids, noncombustible liquids, and pumpable slurry wastes
- Applicability -- All facilities handling liquid wastes
- Assumptions:
  - Separate storage tanks are provided for combustible liquids, noncombustible liquids, and slurry wastes

TABLE 3. NUMBER OF PUMPOUT STATIONS FOR CATEGORY C FACILITIES

Incinerator capacity, Q_{Tmax} (million Btu/hr)	Waste mix	No. of pumpout stations (N_{POS})
50 to 65	Liquids/solids	1
65 to 100	Liquids/solids	2
50 to 65	Liquids only	2
65 to 90	Liquids only	3
90 to 100	Liquids only	4

- Single storage tanks per waste type are desirable for category A facilities, while dual tanks per waste type are desirable for category B facilities. At least two tanks per waste type are needed for category C facilities

- Storage tanks are 5,000, 10,000, and 20,000 gal nominal capacity

- Combustible liquid waste densities are comparable to that of no. 2 fuel oil, approximately 7.2 lb/gal

- Noncombustible liquid and slurry waste densities are comparable to that of water, approximately 8.3 lb/gal

- Category A and B facilities provide 72-hour storage for liquid wastes, whereas category C facilities provide 10-day storage to provide for inconsistencies in waste delivery

- Working relationships -- Calculate each of the following:

  - For category A and B facilities, storage capacity requirements for combustible liquids (WCL), noncombustible liquids (WNL), and slurry wastes (WPS) are calculated by the following relationships:

    $M_{WCL} = 10\ F_{WCL}$ = ______________ gal

    $M_{WNL} = 8.6\ F_{WNL}$ = ______________ gal

    $M_{WPS} = 8.6\ F_{WPS}$ = ______________ gal

  - For category C facilities, equivalent storage capacity requirements are calculated by the following relationships:

    $M_{WCL} = 33.2\ F_{WCL}$ = ______________ gal

    $M_{WNL} = 28.8\ F_{WNL}$ = ______________ gal

    $M_{WPS} = 28.8\ F_{WPS}$ = ______________ gal

  - Storage capacity requirements versus tank numbers and tank capacities for any given type of waste, are presented in Table 4.

  - Based on this table and the preceding calculations, total storage tank requirements are:

TABLE 4. TANK NUMBERS AND CAPACITIES BASED ON FACILITY STORAGE REQUIREMENTS FOR A GIVEN WASTE TYPE

Storage capacity M_i (gal)	No. of 5,000-gal tanks (N_{ST5})	No. of 10,000-gal tanks (N_{ST10})	No. of 20,000-gal tanks (N_{ST20})
0 to 5,000	1	0	0
5,000 to 10,000	2	0	0
10,000 to 15,000	1	1	0
15,000 to 20,000	0	2	0
20,000 to 30,000	2	2	0
30,000 to 40,000	0	0	2
40,000 to 60,000	0	2	2
60,000 to 80,000	0	0	4
80,000 to 100,000	0	2	4
100,000 to 120,000	0	0	6
120,000 to 160,000	0	0	8
160,000 to 200,000	0	0	10
200,000 to 240,000	0	0	12
240,000 to 280,000	0	0	14
280,000 to 320,000	0	0	16
320,000 to 360,000	0	0	18
360,000 to 400,000	0	0	20

	$(N_{ST})_i$ values		
M_i	$(N_{ST5})_i$	$(N_{ST10})_i$	$(N_{ST20})_i$
M_{WCL}			
M_{WNL}			
M_{WPS}			
Total			

3.3.1.3 Liquid Waste Blend Tanks

- Purpose and limitations -- This subsection estimates blending or day batch tank requirements for category C facilities, where numerous combustible and noncombustible liquid waste streams are blended with compatible counterparts to produce mixtures capable of sustaining combustion (e.g., 8,000 Btu/lb blends).
- Applicability -- Category C facilities

- Assumptions:

  -- Only category C facilities, >50 million Btu/hr, employ blend tanks. Category A and B facilities, burning wastes generated in-house, blend in storage as much as possible and feed directly from storage tanks.

  -- All blend tanks are 10,000 gal, providing 6- to 12-hour burn capacities each for 50 to 100 million Btu/hr units operating at 100 percent capacity on 8,000 Btu/lb blends of liquid waste

  -- Four blend tanks are standard for category C facilities, two for high-Btu organic wastes and two for low-Btu aqueous wastes

  -- However, two blend tanks are sufficient for smaller category C facilities (approximately 50 million Btu/hr) burning at least 50 percent solid wastes

- Working relationship -- Based on these assumptions, the numbers of 10,000-gal blend tanks needed in category C facilities are:

  N_{BT} = 4, for all cases, except,

  N_{BT} = 2, for smaller category C facilities (50 million Btu/hr) burning mostly (or at least 50 percent) solid wastes

3.3.1.4 Fuel Oil Storage Tanks

- Purpose and limitations -- Fuel oil storage capacities are quite flexible, particularly for category A and B facilities, because delivery schedules and bulk storage capabilities for the main plant can influence when deliveries are made to the incinerator facility. For the purposes of this study, the approximations listed below should provide sufficient accuracy.

- Applicability -- All facilities

- Assumptions:

  -- Maximum fuel oil demand occurs during startup periods, when auxiliary fuel burners may be modulated upwards over a 2- to 3-day period to cure new refractory

  -- Conservatively assuming a near maximum firing rate over a 2-day period, the fuel oil consumption for a 50 million Btu/hr facility would approach 20,000 gal, leaving some margin for deplume burner operation, if used

  - -- Roughly proportional fuel oil storage capacity is required for smaller and larger facilities

- Working relationship -- Based on these assumptions, fuel oil storage tank versus incinerator capacity requirements are presented in Table 5.

From Table 5,

N_{FO5} = ____________

N_{FO10} = ____________

N_{FO20} = ____________

3.3.1.5 Caustic Soda Solution Storage Tanks

- Purpose and limitations -- Like fuel oil, caustic soda solution (50 weight percent) delivery schedules are variable. Actual consumption rates, calculated in Section 3.7 under scrubbing system analysis, depend on incinerator capacity and the chlorine content of the waste mix. However, reasonable allowances for caustic soda solution storage are similar to those for fuel oil storage.

- Applicability -- All facilities burning chlorinated wastes

- Working relationship -- See results of the analysis in Section 3.3.1.4, substituting N_{CSS} values for N_{FO} values

TABLE 5. NUMBER AND CAPACITY OF FUEL OIL TANKS

Incinerator capacity, Q_{Tmax} (million Btu/hr)	No. of 5,000-gal tanks (N_{FO5})	No. of 10,000-gal tanks (N_{FO10})	No. of 20,000-gal tanks (N_{FO20})
0 to 10	1	0	0
10 to 25	0	1	0
25 to 40	1	1	0
40 to 50	0	0	1
50 to 75	0	1	1
75 to 100	0	0	2

N_{CSS5} = ______________

N_{CSS10} = ______________

N_{CSS20} = ______________

3.3.1.6 Liquid Nitrogen Storage and Consumption

- Purpose and limitations -- Liquid nitrogen storage tanks are usually rented from the nitrogen supplier, therefore, costs for the storage system are reflected as O&M costs rather than capital costs. This section focuses on nitrogen consumption requirements rather than storage tank sizing

- Applicability -- All facilities

- Assumptions:

  -- Virtually 100 percent of nitrogen consumption is associated with tank filling and discharge. Nitrogen leakage rates during normal storage are negligible.

  -- In category A and B facilities, liquid wastes pass through storage tanks only, prior to incineration. In category C facilities, liquid wastes pass through holding tanks, storage tanks, and blend tanks, all of which are nitrogen blanketed.

  -- Fuel oil storage tanks are also nitrogen blanketed, but annual throughput for these tanks is not significant compared to annual liquid waste throughput

  -- Liquid waste densities are 7.2 lb/gal for combustibles, and 8.3 lb/gal for aqueous and slurry wastes as previously indicated

- Working relationships:

  -- For category A and B facilities, based on the preceding assumptions, nitrogen consumption rates are given by:

$$q_{LN} = 0.019\ F_{WCL} + 0.016\ (F_{WNL} + F_{WPS})$$

= __________ ft^3/hr

  -- For category C facilities:

$$q_{LN} = 0.056\ F_{WCL} + 0.048\ (F_{WNL} + F_{WPS})$$

= __________ ft^3/hr

3.3.1.7 Tank Agitator Power Requirements

- Purpose and limitations -- The following calculations are designed to estimate agitator power consumption for liquid waste storage tanks in all facilities, and for holding and blend tanks in category C facilities. The actual power consumption for tank agitation in a given facility can vary widely depending on waste delivery schedules, ambient temperatures, and waste viscosities, among other factors. Therefore, the calculations presented below will only yield rough estimates.

- Applicability -- All facilities (burning liquid wastes)

- Assumptions:

  -- Only gentle agitation is required, no violent mixing. Estimated power requirements are 1 hp for 5,000-gal tanks, 2 hp for 10,000-gal tanks, and 3 hp for 20,000-gal tanks. These are very rough numbers because waste viscosity, tank geometry, and agitator design have a substantial effect on the power required. However, these numbers should be reasonably conservative because they are based on agitation of highly viscous liquids.

  -- Holding and storage tanks are agitated only when they are being filled, except during the winter months in cold weather climates when they are agitated continuously to ensure uniform temperature distribution.

  -- Cold weather conditions requiring tank heating, line heating, and continuous agitation of holding and storage tanks are assumed to prevail 3 months of the year in cold weather climates. This assumption is discussed in more detail in Section 3.3.3.6. If a different cold weather period (θ_{CW}) is deemed appropriate by the user, this value should be entered in Section 2.

  -- Blend tanks are continuously agitated, two at a time, regardless of ambient temperature to ensure feed uniformity

  -- Unloading and holding-to-storage transfer pumping rates are 250 gpm. This will be discussed later in this section.

- Working relationships: For warm-climate category A and B facilities, the agitator power requirement (P_{Ag}) is expressed on a continuous basis as:

$$P_{Ag} = \frac{(N_{ST5} + 2N_{ST10} + 3N_{ST20})[0.14\ F_{WCL} + 0.12\ (F_{WNL} + F_{WPS})]}{15{,}000}$$

= ____________ hp

-- For cold climate category A and B facilities:

$$P_{Ag} = (N_{ST5} + 2N_{ST10} + 3N_{ST20})\ X$$

$$\left\{\theta_{CW} + \frac{(1 - \theta_{CW})\ [0.14\ F_{WCL} + 0.12\ (F_{WNL} + F_{WPS})]}{15{,}000}\right\}$$

= ____________ hp

where $\theta_{CW} = \frac{\text{Months of cold weather per year}}{12}$

= 0.25 default value

-- For warm-climate category C facilities:

$$P_{Ag} = \frac{(N_{HT} + 3N_{ST20})\ [0.14\ F_{WCL} + 0.12\ (F_{WNL} + F_{WPS})]}{15{,}000} + 4$$

= ____________ hp

-- For cold-climate category C facilities:

$$P_{Ag} = (N_{HT} + 3N_{ST20})\ X$$

$$\left\{\theta_{CW} + \frac{(1-\theta_{CW})\ [0.14\ F_{WCL} + 0.12\ (F_{WNL} + F_{WPS})]}{15{,}000}\right\} + 4$$

= ____________ hp

3.3.1.8 Tank Heating Requirements

During extended periods of cold weather, tank heating and line heat tracing are often required to maintain low enough waste viscosities for good atomization and/or to prevent water from freezing in delivery lines. The overall heating requirement is largely dependent on the length and size of piping used in the facility, so tank heating requirements are estimated in conjunction with line heat tracing requirements in Section 3.3.3.6.

3.3.2 Pumps

Pumps are required in all incineration facilities to perform numerous functions. In the front-end plant, pumps may be required to perform any or all of the following functions:

- Liquid waste receiving, transfer from holding to storage tanks, transfer from storage to blend tanks, and feeding
- Fuel oil feeding
- Caustic soda solution feeding

This section presents guidelines to estimate the number, capacity, and power requirements of pumps fulfilling each of these functions.

3.3.2.1 Liquid Waste Feed Pumps

- Purpose and limitations -- The following calculations are designed to estimate the number and capacity of feed pumps required for combustible liquid wastes (WCL), noncombustible liquid wastes (WNL), and slurries (WPS). Overall power requirements for pump operation are estimated as well.
- Applicability -- All facilities burning the previously mentioned types of waste
- Assumptions:
  - In category A and B facilities, wastes are fed directly from the storage tanks to the incinerator burners. In category C facilities, wastes are fed from blend tanks.
  - In category A and B facilities, the total number of feed pumps for a given waste type is equal to the number of storage tanks devoted to that waste, unless a single tank is used. In this case, two pumps are required to provide the redundancy necessary to maintain flow in the event of pump failure.
  - In category C facilities, which feed from blend tanks, two pumps are typically required for each waste type
  - Liquid wastes (WCL and WNL) are delivered to the burners through recirculating pump/piping systems. Recycle ratios of 10:1 (externally defined) are maintained to keep constant nozzle pressure on turndown.
  - Pumpable sludges are lanced into kiln or hearth incinerators near the base of the inlet head, but they are not atomized

- Pump discharge pressures are 75 psig for liquid wastes and 50 psig for slurries and/or sludges. Actual discharge pressures will vary depending on waste viscosity, the atomization technique employed, and line pressure drop, which is a function of site-specific logistics.
- Combustible liquid waste densities are comparable to that of no. 2 fuel oil, 7.2 lb/gal
- Noncombustible liquid waste and pumpable sludge densities are comparable to that of water, 8.3 lb/gal
- Feed temperatures are 60°F
- Theoretical pump horsepower: motor horsepower ratio is 0.40. Efficiencies will vary with pump selection and capacity.

- Working relationships:
  - Feed pump capacities, based on the preceding assumptions, are:

$(q_{pump})_{WCL} = 0.0231\ F_{WCL} =$ __________ gpm

$(q_{pump})_{WNL} = 0.02\ F_{WNL} =$ __________ gpm

$(q_{pump})_{WPS} = 0.002\ F_{WPS} =$ __________ gpm

  - For category A and B facilities, the numbers of feed pumps with these capacities are:

$(N_{pump})_{WCL} = (N_{ST})_{WCL} =$ __________

$(N_{pump})_{WNL} = (N_{ST})_{WNL} =$ __________

$(N_{pump})_{WPS} = (N_{ST})_{WPS} =$ __________

unless $(N_{ST})_i = 1$. In this case, and for category C facilities,

$$(N_{pump})_{WCL} = (N_{pump})_{WNL} = (N_{pump})_{WPS} = 2$$

The general relationship for the feed pump power requirement is:

$$(P_{pump})_i = \frac{7.27 \times 10^{-5}\ (\text{Flow, lb/hr})(\text{Developed pressure, psi})}{(\text{Feed density, lb/ft}^3)(\text{Fractional pump/motor efficiency})}$$

where all variables apply to the i^{th} waste stream.

For combustible liquids:

$$(P_{pump})_{WCL} = 2.52 \times 10^{-3} F_{WCL}$$

$$= \underline{\hspace{3cm}} \text{ hp}$$

For noncombustible liquids:

$$(P_{pump})_{WNL} = 2.18 \times 10^{-3} F_{WNL}$$

$$= \underline{\hspace{3cm}} \text{ hp}$$

For pumpable sludges:

$$(P_{pump})_{WPS} = 1.46 \times 10^{-4} F_{WPS}$$

$$= \underline{\hspace{3cm}} \text{ hp}$$

3.3.2.2 Liquid Waste Transfer Pumps

- Purpose and limitations -- This subsection is designed to estimate the numbers, capacities, and total power demand for liquid waste unloading and transfer pumps in category C facilities
- Applicability -- Category C facilities
- Assumptions:
  - One unloading pump is required per pumpout station, or per every two holding tanks for most category C facilities. In smaller facilities handling both liquids and solids, however, two unloading pumps are needed for the single pumpout station to provide redundancy.
  - Unloading pump capacities are 250 gpm, sufficient to unload a 5,000-gal tank truck in approximately 20 min and minimize waiting time. Discharge pressures are 25 psig.
  - A net total of one pump per holding tank is required to transfer wastes from holding to storage tanks. The actual configuration is that dual pumps are shared by two holding tanks to provide redundancy, however, this is equivalent to one pump per tank.
  - Holding-to-storage transfer pumps are sized for 250-gpm operation at 50-psig discharge pressures
  - A net total of one pump per storage tank is required to transfer wastes from storage to blend tanks. Capacities of these pumps are 100 gpm, which allows a 10,000-gal blend of

two waste streams to be prepared in less than 1 hour. Discharge pressures are 50 psig.

- Working relationships:

-- The number and capacity of unloading pumps are:

$(N_{pump})_{UL} = N_{POS} =$ ________________

unless $N_{POS} = 1$. In this case, $(N_{pump})_{UL} = 2$. For all cases,

$(q_{pump})_{UL} = 250$ gpm

-- The number and capacity of holding-to-storage transfer pumps are:

$(N_{pump})_{HT/ST} = N_{HT} =$ ________________

$(q_{pump})_{HT/ST} = 250$ gpm

-- The number and capacity of storage-to-blending transfer pumps are:

$(N_{pump})_{ST/BT} = N_{ST} =$ ________________

$(q_{pump})_{ST/BT} = 100$ gpm

-- Total power requirements for unloading and transfer pump operation are determined by ratio to feed pump power as explained in the next two entries

-- For liquid wastes, WCL and WNL, the multiplier is 0.167. Additive discharge pressures for the three transfer operations are 125 psig, compared to 75 psig for feeding. However, the feed streams are pumped at 10:1 recycle.

-- For slurries, the multiplier is 2.5, based on the ratio of 125 psig additive discharge pressure for the transfer operations to 50-psig feed pressure. Slurry feed is not recirculated.

-- Therefore, the working equation for total transfer pump power demand, on a continuous basis, is:

$$(P_{pump})_{trans} = 0.167\ [(P_{pump})_{WCL} + (P_{pump})_{WNL}] + 2.5\ (P_{pump})_{WPS}$$

$$= \underline{\qquad\qquad} \text{ hp}$$

3.3.2.3 Fuel Oil Feed Pumps

- Purpose and limitations -- This section simply specifies the number of fuel oil feed pumps required. Power requirements for pump operation are estimated in Section 3.4 under combustion system operation, where the continuous fuel oil demand for supplemental heating is calculated. Pump capacity is also determined in Section 3.4

- Applicability -- All facilities

- Assumptions:

  -- Two fuel oil feed pumps will provide sufficient redundancy for all facilities, regardless of the number of storage tanks employed

- Working relationships:

$$(N_{pump})_{FO} = 2$$

3.3.2.4 Caustic Soda Solution Feed Pumps

Caustic soda solution feed pump capacity and power consumption are estimated in Section 3.7 under scrubbing system operation. Two pumps of this capacity are required for redundancy. Therefore:

$$(N_{pump})_{CSS} = 2$$

3.3.3 Piping

Piping requirements for hazardous waste incineration facilities include liquid waste feeding and transfer within the storage complex, fuel oil and caustic soda solution feeding, and nitrogen hookup to storage tanks. The total length of pipe depends on a number of factors, including overall facility size, number of storage tanks, and storage facility layout. Pipe sizes also vary, although they are normally in the 1 to 4 in. nominal diameter range.

The following subsections present guidelines to estimate both pipe length and diameter. The results should be considered rough approximations, however, because actual piping requirements are highly site specific.

3.3.3.1 Liquid Waste Feeding

- Purpose and limitations -- This section presents guidelines to estimate the length and size of pipe required to feed liquid wastes to the incinerator from storage (category A and B facilities) or from blend tanks (category C facilities). These estimates will be only approximate due to the influence of site-specific factors.

- Applicability -- All facilities burning liquid wastes
- Assumptions:
  - -- Pipe diameter is determined by the feed pump capacities $(q_{pump})_{WCL}$, $(q_{pump})_{WNL}$, and $(q_{pump})_{WPS}$, as calculated in Section 3.3.2.1 and the general guide shown in Table 6 (Reference 1).
  - -- Pipe lengths from blending to the incinerator in category C facilities are approximately 100 ft. For category A and B facilities, approximate pipe lengths from storage to the incinerator vary with capacity as indicated in Table 7.
  - -- For liquids, WCL and WNL, recirculating feed systems are used, therefore, the above-stated lengths are doubled
  - -- The number of feed loops for a given type of liquid waste is equal to half the number of feed pumps for that type of waste, $(N_{pump})_i$, determined in Section 3.3.2.1. This is due to the assumption of redundancy in feed pumping system design.
- Working relationships:
  - -- Based on these assumptions, feed pipe diameters for the three liquid waste types are:

$(D_{pipe})_{WCL}$ = ____________ in.

$(D_{pipe})_{WNL}$ = ____________ in.

$(D_{pipe})_{WPS}$ = ____________ in.

TABLE 6. NOMINAL PIPE DIAMETER VERSUS FLOW

Pump capacity, $(q_{pump})_i$ (gpm)	Nominal pipe diameter, $D_{(pipe)i}$ (in.)
0 to 15	1
15 to 70	2
70 to 150	3
150 to 250	4

TABLE 7. PIPE LENGTH VERSUS INCINERATOR CAPACITY

Incinerator capacity, Q_{Tmax} (million Btu/hr)	Appproximate pipe length, $L_{(pipe)}$ (ft)
0 to 15	75
15 to 30	100
30 to 50	125

-- Total piping lengths for the small category A and B facilities (0 to 15 million Btu/hr) are given by:

$(L_{pipe})_{WCL}$ = 75 $(N_{pump})_{WCL}$ = ____________ ft

$(L_{pipe})_{WNL}$ = 75 $(N_{pump})_{WNL}$ = ____________ ft

$(L_{pipe})_{WPS}$ = 37.5 $(N_{pump})_{WPS}$ = ____________ ft

-- For intermediate size category B facilities (15 to 30 million Btu/hr) and category C facilities:

$(L_{pipe})_{WCL}$ = 100 $(N_{pump})_{WCL}$ = ____________ ft

$(L_{pipe})_{WNL}$ = 100 $(N_{pump})_{WNL}$ = ____________ ft

$(L_{pipe})_{WPS}$ = 50 $(N_{pump})_{WPS}$ = ____________ ft

-- And for 30 to 50 million Btu/hr category B facilities:

$(L_{pipe})_{WCL}$ = 125 $(N_{pump})_{WCL}$ = ____________ ft

$(L_{pipe})_{WNL}$ = 125 $(N_{pump})_{WNL}$ = ____________ ft

$(L_{pipe})_{WPS}$ = 62.5 $(N_{pump})_{WPS}$ = ____________ ft

3.3.3.2 Liquid Waste Transfer

- Purpose and limitations -- This section presents guidelines to estimate transfer piping requirements in category C facilities. The transfer operations are receiving to holding, holding to storage, and storage to blending. These operations are not performed in category A and B facilities, as explained previously.

- Applicability -- Category C facilities
- Assumptions:
  - -- Pumping rates are 250 gpm for the first two transfer operations, and 100 gpm for transfer from storage to blending. Corresponding pipe diameters are 4 in. and 3 in. respectively.
  - -- One 40-ft line connects each unloading station to the two holding tanks it services
  - -- Each storage tank can be accessed through two supply lines from the holding area. This redundancy is desirable in the event that one line becomes plugged.
  - -- The total number of supply lines from the holding area to the storage area is equal to half the number of distribution pumps, $(N_{pump})_{HT/ST}$ (see Section 3.3.2.2). This is due to redundancy in the pumping system design.
  - -- For the 20,000-gal storage tanks used in category C facilities, centerline to centerline distance is 30 ft, which allows for reasonable clearance between tanks
  - -- The total number of supply lines from the storage area to the blending area is equal to half the number of transfer pumps, $(N_{pump})_{ST/BT}$. Again, this is due to redundancy in the pumping system design.
  - -- Typical storage-to-blending transfer distances are 100 ft for 50 to 90 million Btu/hr facilities and 125 ft for 90 to 100 million Btu/hr facilities. Obviously, distances will vary with the site-specific storage tank configuration.
- Working relationships:
  - -- Pipe diameters for the various transfer operations are:

$$(D_{pipe})_{UL} = (D_{pipe})_{HT/ST} = 4 \text{ in.}$$

$$(D_{pipe})_{ST/BT} = 3 \text{ in.}$$

  - -- For the unloading operation, total pipe length is given by:

$$(L_{pipe})_{UL} = 40\ N_{POS} = \_\_\_\_\_\_\_\_\_\_ \text{ ft}$$

  - -- Based on the preceding assumptions for holding-to-storage transfer:

$$(L_{pipe})_{HT/ST} = 60\ N_{ST} = \_\_\_\_\_\_\_\_\_\_ \text{ ft}$$

-- For storage-to-blending transfer in 50 to 90 million Btu/hr facilities:

$$(L_{pipe})_{ST/BT} = 50\ (N_{pump})_{ST/BT} = \underline{\hspace{3cm}}\ \text{ft}$$

-- And for 90 to 100 million Btu/hr facilities:

$$(L_{pipe})_{ST/BT} = 62.5\ (N_{pump})_{ST/BT} = \underline{\hspace{3cm}}\ \text{ft}$$

3.3.3.3 Fuel Oil Feeding

- Purpose and limitations -- This section estimates the size and length of piping required to supply fuel oil to the incinerator from storage
- Applicability -- All facilities
- Assumptions:
  - -- Nominal 1-in. diameter pipe should be sufficient even for the largest facilities
  - -- Pipe lengths are usually longer for fuel oil storage-to-incinerator feeding than for liquid waste feeding because fuel oil storage tanks are usually more remote to allow easier delivery truck access. Typical distances are shown in Table 8.
  - -- These distances should be doubled for pipe length estimating purposes because recirculating flow is needed to maintain nozzle pressure on turndown

TABLE 8. FUEL OIL DELIVERY DISTANCES

Facility type	Incinerator capacity, Q_{Tmax} (million Btu/hr)	Distance (ft)
A, small B	0 to 25	75
Large B	25 to 50	100
Small C	50 to 75	150
Large C	75 to 100	200

- Working relationships:
  - For all cases:

    $(D_{pipe})_{FO} = 1$ in.
  - For category A and small category B facilities:

    $(L_{pipe})_{FO} = 150$ ft
  - For large category B facilities:

    $(L_{pipe})_{FO} = 200$ ft
  - For small category C facilities:

    $(L_{pipe})_{FO} = 300$ ft
  - For large category C facilities:

    $(L_{pipe})_{FO} = 400$ ft

3.3.3.4 Caustic Soda Solution Feeding

- Purpose and limitations -- This section estimates pipe size and length requirements for caustic soda solution transfer from storage to the scrubbing system
- Applicability -- All facilities burning chlorinated wastes
- Assumptions:
  - Caustic soda solution storage tanks are located within the liquid waste/fuel oil storage area, and a berm was built for spill control
  - Tank locations are somewhat remote, compared to waste storage, to provide easy access for delivery trucks. However, these locations are not as remote as those for fuel oil storage because caustic soda solution is more difficult to pump than fuel oil. Typical pumping distances are shown in Table 9.
- Working relationships:
  - For all cases:

    $(D_{pipe})_{CSS} = 1$ in.

TABLE 9. CAUSTIC SODA SOLUTION DELIVERY DISTANCES

Facility type	Incinerator capacity, Q_{Tmax} (million Btu/hr)	Distance (ft)
A, small B	0 to 25	50
Large B	25 to 50	75
Small C	50 to 75	100
Large C	75 to 100	150

-- For category A and small category B facilities:

$(L_{pipe})_{CSS}$ = 50 ft

-- For large category B facilities:

$(L_{pipe})_{CSS}$ = 75 ft

-- For small category C facilities:

$(L_{pipe})_{CSS}$ = 100 ft

-- For large category C facilities:

$(L_{pipe})_{CSS}$ = 150 ft

3.3.3.5 Nitrogen Distribution

- Purpose and limitations -- This section presents guidelines to estimate piping requirements for nitrogen distribution for tank blanketing
- Applicability -- All facilities
- Assumptions:
  - Nitrogen blanketing is required for all liquid waste tanks (holding, storage, and blending) and for fuel oil storage tanks
  - Centerline-to-centerline distances between tanks are approximately 30 ft for 20,000-gal tanks, 25 ft for 10,000-gal tanks, and 20 ft for 5,000-gal tanks

- Working relationships:

  -- For all nitrogen delivery cases:

  $$(D_{pipe})_{LN} = 1 \text{ in.}$$

  -- For nitrogen supply, total pipe lengths are given by:

  $$(L_{pipe})_{LN} = 30\ (N_{ST20} + N_{FO20}) + 25\ (N_{ST10} + N_{FO10} + N_{BT}) + 20\ (N_{ST5} + N_{FO5} + N_{HT}) = \underline{\hspace{3cm}} \text{ ft}$$

3.3.3.6 Cold Weather Heating Requirements for Tanks and Piping

- Purpose and limitations -- The objective of this section is to estimate the heating requirements for tanks and delivery lines during extended periods of cold weather. The estimates are approximate due to site-specific variations in tank and piping configurations, cold weather durations, and ambient temperatures during periods of cold weather.

- Applicability -- All facilities located in cold weather climates

- Assumptions:

  -- Although facilities located in warm weather climates may be equipped for tank and line heating in the event of unusually cold weather conditions, the annual heating requirements for these facilities are negligible

  -- In cold weather sites, all liquid waste and caustic soda solution tanks are equipped with suction line or small recirculatory electrical heaters

  -- Liquid waste and caustic soda solution delivery lines are also electrically heat traced

  -- During cold weather conditions, liquid wastes are maintained at a minimum temperature of 40°F

  -- Because 50 percent caustic soda solution begins to crystallize at 54°F (Reference 2), these tanks and lines are maintained at 60°F to provide a safety margin

  -- The extent and severity of cold weather varies considerably from year to year and location to location in the northern United States. Therefore, the user is encouraged to input (in Section 2) appropriate values for cold weather duration (Θ_{CW}) and the average temperature over this duration (T_{CW}). However, reasonably conservative default values are $\Theta_{CW} = 0.25$ yr/yr and $T_{CW} = 20°F$.

- Liquid waste and caustic soda solution tanks are equipped with 4 in. of felt insulation, with thermal conductivity, $k = 0.25$ Btu-in./ft^2-hr-°F (Reference 3)

- All liquid waste and caustic soda solution piping is encased in calcium silicate insulation, with a (conservative) thermal conductivity, $k = 0.39$ Btu-in./ft^2-hr-°F (Reference 3). Insulation thickness is equivalent to nominal pipe diameters (1 to 4 in.).

- Tank height is approximately equal to tank diameter, in all cases

- Heat transfer resistances for the inner convective films in (agitated) tanks and pipes are negligible, as are heat transfer resistances through steel tank shells and pipes

- The outside convective heat transfer coefficient, h_o, for both tanks and pipes is approximately 4 Btu/hr-ft^2-°F (Reference 3)

- General relationships -- From Reference 3, tank and pipe heating requirements are approximated by:

$$\text{(Energy input)} = 1.3\ \text{(Tank heat loss + pipe heat loss)}$$

where the 1.3 factor is a design safety margin.

Heat losses from tank sides and pipes are given by:

$$Q,\text{Btu/hr} = U_o\ A_o\ \Delta T$$

where

U_o = overall heat transfer coefficient based on outside area, Btu/hr-ft^2-°F, and,

$$U_o = \frac{1}{\dfrac{(A_o/L)\ \ln(D_o/D_i)}{2\ \pi\ k} + \dfrac{1}{h_o}}$$

where

A_o = outside surface area, ft^2
L = length or height, ft

Heat losses from tank tops are again given by:

$$Q = U\ A\ \Delta T$$

where

$$U = \frac{1}{\frac{L}{k} + \frac{1}{h_o}}$$

and L = 4 in. insulation thickness

- Working relationships -- Based on these assumptions, the total cold weather heating requirement for tanks and piping in category A and B facilities is given by:

$$\begin{aligned} P_{heat} = 5.1 \times 10^{-4}\, \theta_{CW} \Big[\big\{ & 22.3\, N_{ST5} + 35.2\, N_{ST10} + 55.6\, N_{ST20} \\ & + 0.2\, [(L_{pipe})_{WCL} + (L_{pipe})_{WNL} \\ & + (L_{pipe})_{WPS}] \big\} (40 - T_{CW}) \\ & + \big\{ 22.3\, N_{CSS5} + 35.2\, N_{CSS10} + 55.6\, N_{CSS20} \\ & + 0.2\, (L_{pipe})_{CSS} \big\} (60 - T_{CW}) \Big] = \underline{\qquad\qquad} \text{ hp} \end{aligned}$$

-- For category C facilities:

$$\begin{aligned} P_{heat} = 5.1 \times 10^{-4}\, \theta_{CW} \Big[\big\{ & 22.3\, (N_{ST5} + N_{HT}) \\ & + 35.2\, (N_{ST10} + N_{BT}) + 55.6\, N_{ST20} + 0.2\, [(L_{pipe})_{WCL} \\ & + (L_{pipe})_{WNL} + (L_{pipe})_{WPS} + (L_{pipe})_{UL} + (L_{pipe})_{HT/ST} \\ & + (L_{pipe})_{ST/BT}] \big\} (40 - T_{CW}) + \big\{ 22.3\, N_{CSS5} + 35.2\, N_{CSS10} \\ & + 55.6\, N_{CSS20} + 0.2\, (L_{pipe})_{CSS} \big\} (60 - T_{CW}) \Big] \\ = \underline{\qquad\qquad} \text{ hp} \end{aligned}$$

3.3.4 Carts

- Purpose and limitations -- In category A and B facilities, carts are used to deliver, store, and transfer bulk solid wastes. The purpose of this subsection is to estimate the numbers and sizes of carts required to fulfill this function.

- Applicability -- All category A and B facilities handling bulk solid wastes

- Assumptions:

  -- Approximately 16 carts are needed for each incineration facility burning bulk solids to provide flexibility in delivery from processing to waste disposal facilities

- -- Carts are sized to transport approximately 1 hr of bulk solids feed to the incinerator feed hopper

- -- Heat input with the bulk solids feed is given by,

$$Q_{WBS} = F_{WBS}\ (HV)_{WBS}$$

- -- Corresponding cart capacities versus bulk solids heat input rates are shown in Table 10.

- Working relationships:

  - -- Based on these assumptions, the number of carts required is:

$$N_{cart} = 16$$

  - -- The bulk solids heat input rate is:

$$Q_{WBS} = F_{WBS}\ (HV)_{WBS} = \_\_\_\_\_\_\_\_ \text{ Btu/hr}$$

  - -- Cart capacities (M_{cart}) versus bulk solids heat input rates shown in Table 11. From Table 11,

$$M_{cart} = \_\_\_\_\_\_\_\_ \text{ yd}^3$$

3.3.5 Vehicles

- Purpose and limitations -- The purposes of this section are to estimate (1) the number of cart-dumping forklifts required to handle bulk solids in category A and B facilities, (2) the number of lift trucks required to handle drummed wastes in category C facilities, and (3) the operating requirements for these vehicles

TABLE 10. CART CAPACITY VERSUS BULK SOLIDS HEAT INPUT

Individual cart capacity (yd^3)	Heat input with bulk solids, Q_{WBS} (million Btu/hr)
0.5	5
1	10
2	20
3	30
4	40
5	50

TABLE 11. CART CAPACITY REQUIREMENTS

Cart capacity, M_{cart} (yd^3)	Heat input with bulk solids, Q_{WBS} (million Btu/hr)
0.5	1 to 5
1	5 to 10
2	10 to 20
3	20 to 30
4	30 to 40
5	40 to 50

- Applicability -- All facilities handling solid wastes
- Assumptions:
  - -- Two cart transport vehicles are needed for category A and B facilities, one to handle normal transfer operations and one spare
  - -- For category C facilities, four lift trucks are needed: two to handle incoming drummed wastes, one to place drums on the incinerator feed conveyor, and one spare
  - -- Time allotments for cart unloading from the delivery truck, deployment in the storage area, pickup, and dumping into the incinerator feed hopper are 30 sec each, or 2 min total per cart
  - -- Round-trip distances from the unloading dock to the storage area and from the storage area to the process area are 100 ft and 200 ft, respectively, for a total transport distance of 300 ft. At 5 mph, this translates to a total round-trip time of 40 to 45 sec per cart.
  - -- Allowing an additional 2 to 3 min for idle time, operator instruction, and potential distractions, the total vehicle operating time is approximately 6 min per cart of waste

  - As assumed in Section 3.3.4, carts are sized to carry 1 hr of bulk solids feed. Thus, vehicle operating time is 6 min per hour on the average, or 10 percent of the facility operating time.

  - In category C facilities, lift trucks are used to transfer drums of waste from the receiving dock to an appropriate location in the storage area. Each lift truck handles one four-drum pallet per trip.

  - Approximately 2 min are needed for pickup and transport through the warehouse to a location, which translates to an average time requirement of 30 sec per drum

  - An additional 90 sec are allotted for drum selection, pickup, and loading onto the drum feed conveyor in the warehouse area

  - Allowing an additional 2 to 3 min per drum for operator instruction, idle time, and potential distractions, the total vehicle operating time is approximately 5 min per drum

  - Each drum contains approximately 450 lb of waste

- Working relationships:

  - For category A and B facilities, the required number of vehicles is:

    $N_{veh} = 2$

  - For category C facilities, $N_{veh} = 4$

  - Vehicle operating time, expressed as hours per hour of facility operation, is:

    - For category A and B facilities:

      $\theta_{veh} = 0.1$ hr/hr

    - For category C facilities:

      $\theta_{veh} = 1.85 \times 10^{-4} F_{WCS} =$ _______________ hr/hr

3.3.6 Bulk Solid Waste Conveyors

- Purpose and limitations -- This section presents guidelines to estimate capacities, lengths, and power requirements for bulk solid waste conveyors used in category C facilities

- Applicability -- Category C facilities handling bulk solid wastes

- Assumptions:

  -- In category C facilities, bulk solids are transported to the incinerator feeder by conveyor system rather than in carts

  -- The assumed conveyor system includes (1) an underdrag screw conveyor to remove solids from the storage pit, (2) a bucket elevator, and (3) an elevated, enclosed belt conveyor to access the incinerator feed hopper

  -- Screw conveyor lengths are 75 ft for larger category C facilities (75 to 100 million Btu/hr) and 50 ft for smaller facilities (50 to 75 million Btu/hr)

  -- Bucket elevator heights are 25 ft

  -- Belt conveyor lengths are 50 ft

  -- Weight capacities are determined by the bulk solids feedrate, F_{WBS}, but should not exceed 2 to 3 ton/hr

  -- Solids density is 50 lb/ft^3

  -- For screw conveyors with pipe-mounted sectional spiral flights carrying 31 percent of their cross-section of 50 lb/ft^3 material over a maximum distance of 75 ft, typical motor requirements are 3 hp for up to 10,000 lb/hr capacities

  -- For a horizontal belt conveyor 50 ft in length handling 50 lb/ft^3 material at a maximum capacity of 32,000 lb/hr (several times normal incinerator feed system requirements), the motor horsepower requirement is nominally 2 hp. This includes terminal and belt-driven tripper losses.

  -- For bucket elevators with spaced buckets and digging boots, approximate horsepower requirements are given by the relationship:

$$\text{Power, hp} = \frac{[\text{Capacity (lb/hr)}]\ [\text{Lift (ft)}]}{10^6}$$

  which includes normal drive and pick-up loading losses. For the range of conditions addressed in this study, however, a 1-hp drive can be assumed for all cases.

- Working relationships:

  -- Weight capacities for the conveying system components are given by:

$$(F_{conv})_{WBS} = F_{WBS}/2{,}000 = \underline{\hspace{3cm}} \text{ tons/hr}$$

-- Volumetric capacities are given by:

$(q_{conv})_{WBS} = F_{WBS}/50 =$ ______________ ft^3/hr

-- Power requirements are approximated by:

$(P_{conv})_{WBS} = 6$ hp

3.3.7 Bulk Solid Waste Feeders

- Purpose and limitations -- Ram feeders are used in virtually all hazardous waste incineration facilities to inject bulk solids into the combustion chamber. This subsection presents guidelines to estimate hopper capacities and power requirements for these ram feeders.

- Applicability -- All facilities burning bulk solid wastes

- Assumptions:

  -- Typical feed hopper volumes versus bulk solids heat input rates are shown in Table 12

  -- Hydraulic power unit ratings are typically 5 hp for ram feeders servicing incinerators with nominal solids feed capacities of 2,500 lb/hr or 20 million Btu/hr (up to 30 million Btu/hr including liquid wastes). Assumed power unit ratings for larger incinerators are:

    - 7.5 hp for up to 40 million Btu/hr solids capacity and 65 million Btu/hr total capacity

    - 10 hp for up to 60 million Btu/hr solids capacity and up to 90 to 100 million Btu/hr total capacity

- Working relationships:

  -- Based on these simple guidelines, the feed hopper capacity, M_{hop}, and feeder power requirement, $(P_{feed})_{WBS}$, can be recorded directly:

$M_{hop} =$ ______________ yd^3

$(P_{feed})_{WBS} =$ ______________ hp

3.3.8 Drum Elevators/Conveyors

- Purpose and limitations -- This section presents guidelines to size and estimate the power requirements for semiautomatic drummed waste conveying systems used in category C facilities. These

TABLE 12. FEED HOPPER VOLUME VERSUS BULK SOLIDS HEAT INPUT RATE

Hopper volume (yd^3)	Heat input with bulk solids, Q_{WBS} (million Btu/hr)
0.5	1 to 5
1	5 to 10
2	10 to 20
3	20 to 30
4	30 to 40
5	$\geq$50

guidelines are only approximate because actual conveyor system layout is extremely site specific.

- Applicability -- Category C facilities burning drummed wastes
- Assumptions:
  - In large category C rotary kiln incineration facilities (50 to 100 million Btu/hr), 55-gal drums are the predominant waste container
  - Each drum of waste weighs 450 lb
  - Drums are stored in a warehouse on pallets, four drums to a pallet. They are grouped in sections 4 drums wide by 16 drums long as shown in Figure 11, with 8-ft spacings between each section to allow lift truck access. Stacking is avoided for safety reasons.
  - As needed, drums are loaded by lift truck onto an indexing roller conveyor system which runs the length of the warehouse, as shown in Figure 12. The two longitudinal spurs of this conveyor system converge at the center of the warehouse, where drums automatically transfer to a perpendicular spur which leads out of the warehouse to the process area.
  - For large category C facilities, the total length of this conveyor system is 250 ft. For small facilities, the total length is 150 ft. The basis for these assumed lengths is the

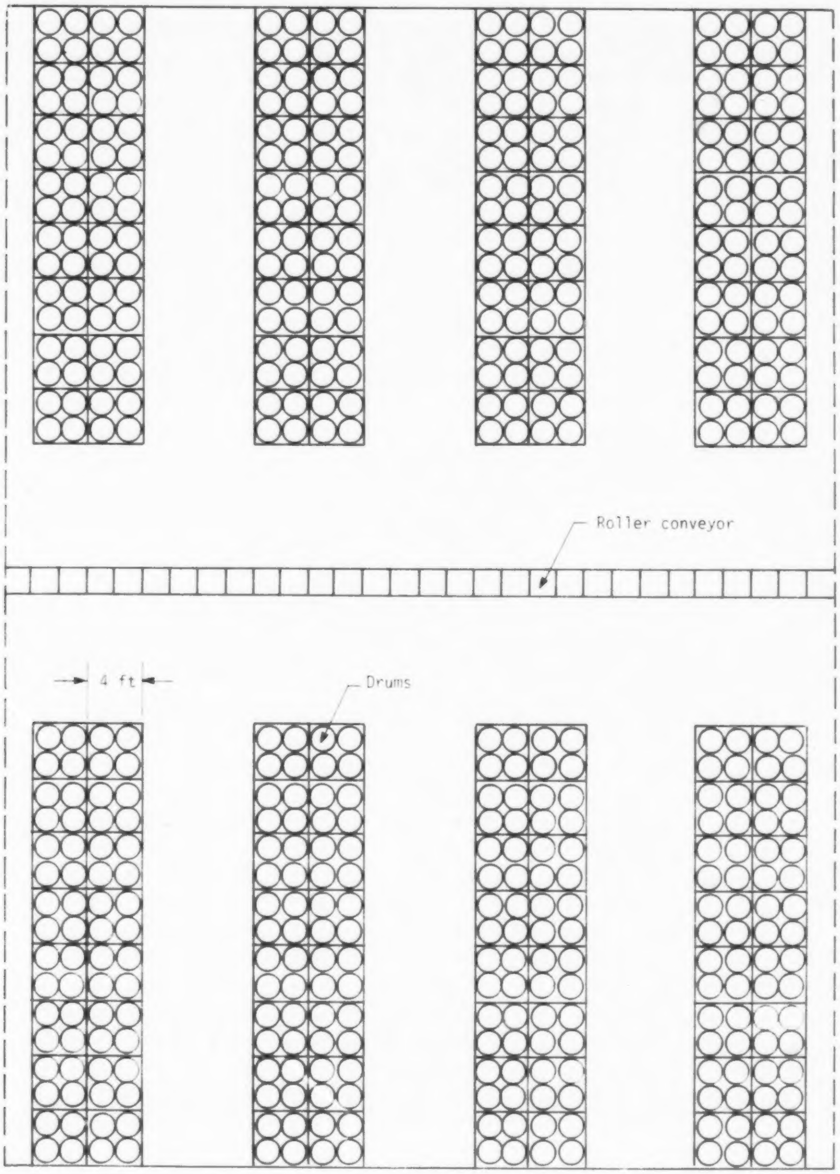

Roller conveyor
4 ft
Drums

Figure 11. Hypothetical drum warehouse cross section.

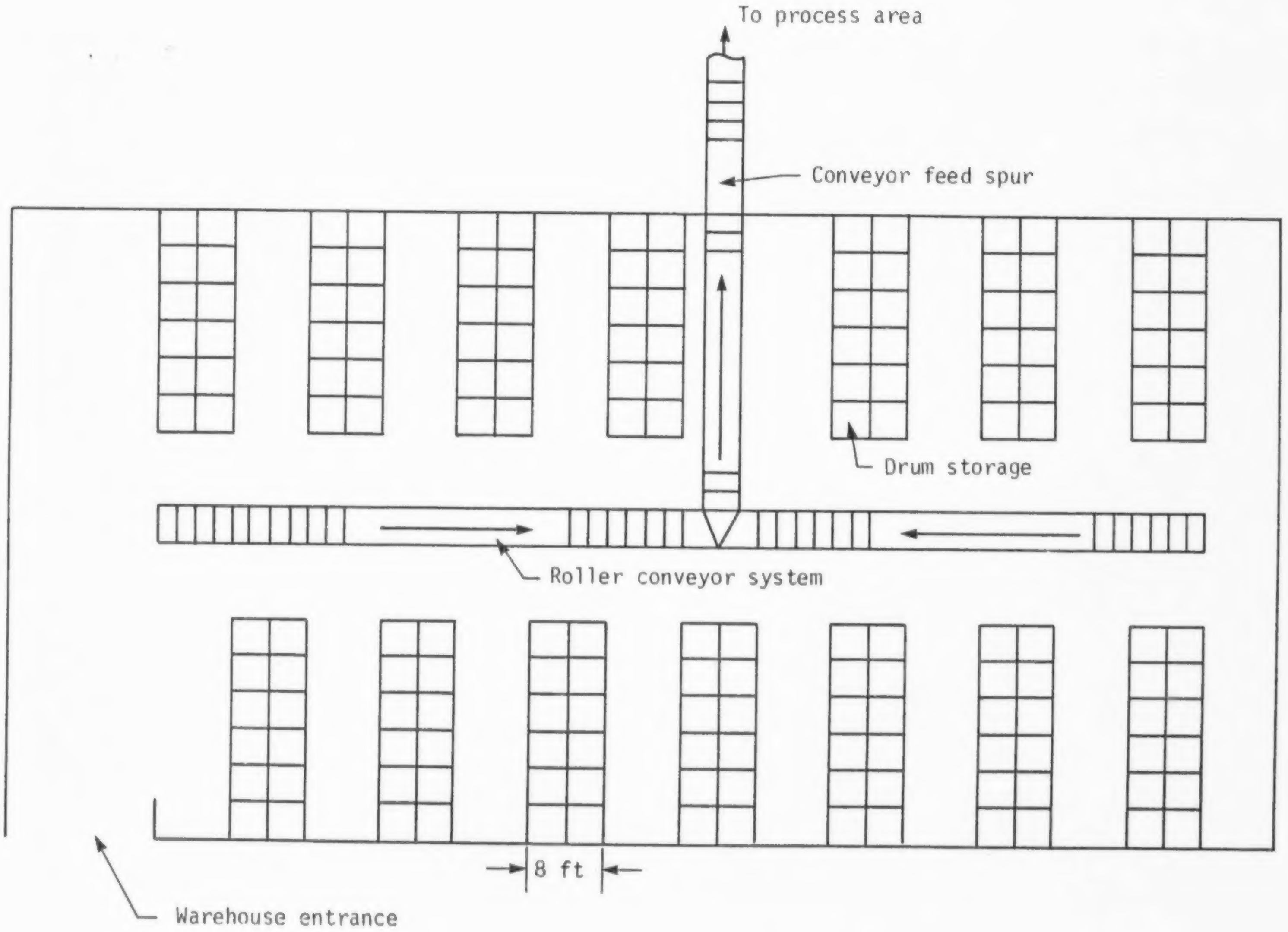

To process area
Conveyor feed spur
Drum storage
Roller conveyor system
8 ft
Warehouse entrance

Figure 12. Hypothetical drum warehouse overview.

estimated warehouse space requirement discussed in Section 3.3.10.

-- At the edge of the process area, a 25-ft drum elevator lifts the drums to a position where they can be fed to the kiln through a double-airlock, tipping table, drop chute configuration

-- For the three-spur roller conveyor system, assuming conservative overdesign allowances, the connected horsepower is approximately 10 hp

-- Drum elevator power requirements can be estimated by the relationships:

$$\text{Power, hp} = \frac{[\text{Drum feed capacity (lb/hr)}]\ [\text{Lift (ft)}]}{10^6}$$

For the range of conditions addressed in this study, however, a 1-hp drive can be assumed for all cases.

- Working relationships:

  -- The conveying system capacity, expressed in tons per hour, is given by:

  $(F_{conv})_{WCS} = F_{WCS}/2,000 =$ ___________ ton/hr

  -- In terms of drums per hour, capacities are:

  $N_{WCS} = F_{WCS}/450 =$ ___________ drum/hr

  -- Roller conveyor lengths are listed in Table 13.

  -- From Table 13,

  $(L_{conv})_{WCS} =$ ___________ ft

  -- Power requirements are given by:

  $(P_{conv/feed})_{WCS} = 11$ hp

3.3.9 Compressors

- Purpose and limitations -- In many hazardous waste incinerators, liquid wastes are broken into droplets at the burner using external air or steam atomization. Both methods have their advantages and disadvantages, so the combustion characteristics of the waste usually dictate the choice between these alternatives. For the purposes of this study, however, high pressure air atomization is assumed for all cases. This assumption will not

TABLE 13. ROLLER CONVEYOR LENGTH VERSUS DRUMMED WASTE FEEDRATE

Roller conveyor length, $(L_{conv})_{WCS}$ (ft)	Drum feedrate, N_{WCS} (drum/hr)
150	≤ 5
200	5 to 7.5
250	7.5 to 10

significantly impact the overall cost estimate, and it simplifies the tedious material balance calculations for combustion system operation presented in Section 3.4.

The purpose of this section is to estimate the atomizing air requirements for burner operation, and thus, to size the compressor for subsequent capital cost estimation in Section 4. Compressor power requirements are also estimated.

- Applicability -- All facilities burning liquid wastes
- Assumptions:
  - -- High-pressure air atomization is used for liquid wastes and fuel oil, but not for slurry wastes (WPS) which are lanced into the incinerator
  - -- Liquid wastes are externally atomized, while fuel oil is internally atomized
  - -- Atomizing air requirements for liquid wastes are assumed to be 0.5 lb/lb feed, a liberal allowance which should cover the comparatively minimal requirements for fuel oil atomization
  - -- Air enters the compressor at 60°F, 14.7 psia, and a specific volume of 13.09 ft^3/lb
  - -- Compressor discharge pressure is 100 psig
  - -- Overall isothermal compression/motor efficiency is 40 percent

- -- The general motor horsepower relationship is:

$$\text{Power (hp)} = \frac{4.36 \times 10^{-3}\ [\text{Inlet pressure (psia)}][\text{Volumetric air flow (cfm)}]\ \ln\left(\frac{\text{Discharge pressure (psia)}}{\text{Inlet pressure (psia)}}\right)}{(\text{Isothermal compression/motor efficiency})}$$

- Working relationships:
  - -- Atomizing air flow requirements and compressor capacity are given by:

$(F_{air})_{comp} = 0.5\ (F_{WCL} + F_{WNL}) =$ ____________ lb/hr

$(q_{air})_{comp} = 0.218\ (F_{air})_{comp} =$ ____________ scfm

  - -- The motor horsepower is then given by:

$P_{comp} = 0.329\ (q_{air})_{comp} =$ ____________ hp

3.3.10 Buildings

Common structural requirements for category A and B facilities include a small warehouse to store carts full of bulk solid waste, a compressor house, and a control room. For category C facilities, structural requirements include an enclosure to house the tank truck unloading pumps (and personnel coordinating the receiving operation), a warehouse to enclose the bulk solids storage area, a drum storage warehouse, a compressor house, and a larger building for the control room, laboratory, and offices. The following subsections present guidelines for estimating the square footage needed for each of these structures.

3.3.10.1 Pumpout Station Enclosures

- Purpose and limitations -- Simple enclosures of sheet steel construction are frequently provided in category C facilities to house the tank truck pumpout stations and provide cover for personnel directing the waste unloading operation. This subsection presents guidelines to estimate the space requirements for such structures.
- Applicability -- Category C facilities
- Assumptions:
  - -- The relationship between number of pumpout stations, waste mix, and incinerator capacity is shown in Table 3 in Section 3.3.1.1.
  - -- All pumpout station enclosures are 10 ft wide

-- Enclosure length is approximately 15 ft per pumpout station

- Working relationships -- Based on these assumptions square footage requirements (A_{POS}) are given by:

  $A_{POS} = 150\ N_{POS} =$ __________ ft^2

3.3.10.2 Bulk Solid Waste Storage Enclosures

- Purpose and limitations -- For facilities storing bulk solid wastes in carts (categories A and B) or in pits (category C), it is good design practice to provide a warehouse to protect these wastes and the equipment/personnel handling them from the elements. This subsection provides guidelines to estimate the floor space required for these warehouses.

- Assumptions:

  -- For category A and B facilities, cart capacities are approximately 1 yd^3/10 million Btu/hr bulk solids heat input rate expressed in Section 3.3.4

  -- Cart dimensions are cubic (e.g., a 1-yd^3 cart is 3 ft x 3 ft x 3 ft)

  -- No more than 8 full carts of the 16 carts allotted for each facility need to be stored in the warehouse at any given time. The remaining carts are assumed to be empty or at the plant processing area being filled.

  -- In the warehouse, the eight full carts are arranged in a four-cart by two-cart configuration with 1-ft spacing in between carts and 8 ft on all perimeters to allow for vehicle access

  -- In category C facilities, bulk solid wastes are stored in 10-ft deep pits volumetrically sized for 3 days storage capacity

  -- Solids density is 50 lb/ft^3

  -- On each side and at the back of the storage pit, 20 ft are allotted for service access (to the underdrag screw conveyor system)

- Working relationships -- Based on the preceding assumptions, space requirements for bulk solids storage warehouses versus incinerator facility types and bulk solids feedrates are shown in Table 14.

TABLE 14. BULK SOLIDS STORAGE WAREHOUSE SIZES

Facility category	Heat input with bulk solids, Q_{WBS} (million Btu/hr)	Building dimensions (ft x ft)	Area, A_{WBS} (ft^2)
A	1 to 5	25 x 30	750
A/B	5 to 20	25 x 35	875
B	20 to 50	30 x 40	1,200
C	50	50 x 70	3,500
C	50 to 75	55 x 75	4,125
C	75 to 100	60 x 80	4,800

-- From Table 14,

A_{WBS} = __________ ft^2

3.3.10.3 Drum Storage Enclosures

- Purpose and limitations -- Drum storage warehouses are commonly provided for category C facilities burning containerized wastes. This subsection provides guidelines to estimate the floor space required for this type of storage.
- Applicability -- Category C facilities handling drummed wastes
- Assumptions:
  - As indicated in Section 3.3.8, drums are stored in groups of 64, in 4-drum by 16-drum groupings with equal space allotted between groupings for lift truck access
  - In all cases, warehouse width is equal to 84 ft; 32 ft for drum storage columns on the front and back sides, and 20 ft in the middle for the conveyor system and lift truck access
  - Warehouse length is determined by the total number of drums stored, the 16-ft requirement per grouping of drums (8 ft for each four-drum cross section, and 8 ft of clearance) on both the front and back sides of the warehouse, and the assumed

20-ft requirement for vehicle entry at the end of the warehouse where wastes are received

- -- The total number of drums stored is equivalent to 5 days incinerator feedrate

- Working relationships:

  - -- Total drum storage capacity is given by:

    $M_{WCS} = 120\ N_{WCS} = \_\_\_\_\_\_\_\_\_\_$ drums

  - -- Warehouse length is then given by:

    $(L_{Wh})_{WCS} = 20 + 0.125\ M_{WCS} = \_\_\_\_\_\_\_\_\_\_$ ft

  - -- Warehouse width = 84 ft, therefore:

    Total warehouse space, $A_{WCS} = 84\ (L_{Wh})_{WCS}$

    $= \_\_\_\_\_\_\_\_\_\_$ ft^2

3.3.10.4 Compressor Enclosures

- Purpose and limitations -- This section presents estimated space requirements for compressor housing

- Applicability -- All facilities

- Assumptions/working relationships:

  - -- For all facilities, a 20 ft x 20 ft or 400-ft^2 enclosure is sufficient to house the compressor. Therefore,

    $A_{comp} = 400\ ft^2$

3.3.10.5 Control Room and Auxiliaries

- Purpose and limitations -- This section presents estimated space requirements for control rooms in category A and B facilities, and combined control room/laboratory/office buildings for category C facilities

- Applicability -- All facilities

  - -- For category A and B facilities, 30 ft x 30 ft, or 900-ft^2 control rooms are assumed. Therefore,

    $A_{CR} = 900\ ft^2$

-- For category C facilities, a laboratory and offices are also needed, expanding building capacity to 30 ft x 100 ft, or 3,000 ft^2. Thus, A_{CR} = 3,000 ft^2

3.4 COMBUSTION SYSTEM OPERATION

As indicated in Section 2, three types of generic incinerator designs are commonly used for hazardous waste disposal: (1) liquid injection incinerators handling liquids only, (2) rotary kiln incinerators for liquid, bulk solid, and drummed wastes, and (3) multiple chamber, hearth-type incinerators for liquids and bulk solids. The sizing and design of these units are largely determined by the input data specified in Section 2, and state-of-the-art design practices discussed in conjunction with capital costs in Section 4. Therefore, this section deals primarily with incinerator operating requirements, including:

- Low-fire flame stabilization, supplemental heating, and startup fuel requirements
- Combustion air flow and blower power requirements
- Fuel oil feed pump capacity and power requirements
- Charge stoking and bottom ash handling requirements

Combustion gas flow and composition leaving the incinerator are also estimated to aid in the analysis of downstream equipment design and operation.

3.4.1 Waste Component Feedrates and Gross Heat Input

- Purpose and limitations -- These calculations provide the basis for many subsequent material and energy balance calculations. Any limitations in accuracy are due solely to the quality of the input data.
- Applicability -- All facilities
- Assumptions -- None. Calculations are based solely on material balance.
- General equations:

  -- Gross heat input with waste:

$$Q_W = \Sigma \, (F_{Wi}) \, (HV_{Wi})$$

where subscript i refers to the ith waste stream

-- Elemental components-in-waste feedrates:

$$(F_k)_W = \Sigma (F_{Wi}) [(X_k)_{Wi}]$$

where subscript i refers to the ith waste stream and subscript k refers to the kth elemental component

- Working equations:

-- $Q_W = (F_{WCL}) (HV_{WCL}) + (F_{WNL}) (HV_{WNL}) + (F_{WPS}) (HV_{WPS})$

$+ (F_{WBS}) (HV_{WBS}) + (F_{WCS}) (HV_{WCS}) =$ ______ Btu/hr

-- Carbon-in-waste feedrate:

$(F_C)_W = (F_{WCL}) [(X_C)_{WCL}] + (F_{WNL}) [(X_C)_{WNL}] + (F_{WPS}) [(X_C)_{WPS}]$

$+ (F_{WBS}) [(X_C)_{WBS}] + (F_{WCS}) [(X_C)_{WCS}]$

= ____________ lb/hr

-- Hydrogen-in-waste feedrate:

$(F_{H_2})_W = (F_{WCL}) [(X_{H_2})_{WCL}] + (F_{WNL}) [(X_{H_2})_{WNL}]$

$+ (F_{WPS})[(X_{H_2})_{WPS}] + (F_{WBS}) [(X_{H_2})_{WBS}]$

$+ (F_{WCS}) [(X_{H_2})_{WCS}] =$ ____________ lb/hr

-- Oxygen-in-waste feedrate:

$(F_{O_2})_W = (F_{WCL})[(X_{O_2})_{WCL}] + (F_{WNL})[(X_{O_2})_{WNL}] + (F_{WPS})[(X_{O_2})_{WPS}]$

$+ (F_{WBS}) [(X_{O_2})_{WBS}] + (F_{WCS}) [(X_{O_2})_{WCS}]$

= ____________ lb/hr

-- Nitrogen-in-waste feedrate:

$(F_{N_2})_W = (F_{WCL})[(X_{N_2})_{WCL}] + (F_{WNL})[(X_{N_2})_{WNL}] + (F_{WPS})[(X_{N_2})_{WPS}]$

$+ (F_{WBS}) [(X_{N_2})_{WBS}] + (F_{WCS}) [(X_{N_2})_{WCS}]$

= ____________ lb/hr

-- Chlorine-in-waste feedrate:

$(F_{Cl})_W = (F_{WCL})[(X_{Cl})_{WCL}] + (F_{WNL})[(X_{Cl})_{WNL}] + (F_{WPS})[(X_{Cl})_{WPS}]$

$+ (F_{WBS}) [(X_{Cl})_{WBS}] + (F_{WCS}) [(X_{Cl})_{WCS}]$

= ____________ lb/hr

-- Moisture-in-waste feedrate:

$$(F_{H_2O})_W = (F_{WCL}) [(X_{H_2O})_{WCL}] + (F_{WNL}) [(X_{H_2O})_{WNL}] + (F_{WPS})[(X_{H_2O})_{WPS}] + (F_{WBS}) [(X_{H_2O})_{WBS}] + (F_{WCS}) [(X_{H_2O})_{WCS}] = \underline{\qquad\qquad} \text{ lb/hr}$$

-- Ash-in-liquid-waste feedrate:

$$(F_{ash})_{WL} = (F_{WCL}) [(X_{ash})_{WCL}] + (F_{WNL}) [(X_{ash})_{WNL}] = \underline{\qquad\qquad} \text{lb/hr}$$

-- Ash-in-slurry-and-solid-waste feedrate:

$$(F_{ash})_{WS} = (F_{WPS}) [(X_{ash})_{WPS}] + (F_{WBS}) [(X_{ash})_{WBS}] + (F_{WCS}) [(X_{ash})_{WCS}] = \underline{\qquad\qquad} \text{ lb/hr}$$

3.4.2 Low-Fire Fuel Consumption Rate

- Purpose and Limitations -- These calculations estimate the quantities of auxiliary fuel needed to maintain good flame stability in liquid waste burners. These fuel requirements do not include potential supplemental heating requirements to maintain temperature. Any limitations in accuracy are subject to the constraints outlined below.

- Applicability -- In actual practice, auxiliary fuel burners do not need to be operated at low fire to maintain flame stability if

  -- Fuel-quality liquid wastes are being burned

  -- Well-blended wastes (even in the 5,000 to 8,000 Btu/lb range) are being fired in high-efficiency burners

  However, many wastes with average heating values in the self-combustible range are not completely homogeneous as fired. In these situations, slugs of water or other inerts passing through the burner can cause flame-sensor-initiated shutdown of the system. This occurrence can be prevented by cofiring small quantities of fuel with the waste.

  For conservative cost estimating purposes, it may be assumed that flame-stabilizing fuel consumption is needed when liquid wastes with heating values less than 8,000 to 10,000 Btu/lb are fired through the main burner.

- Assumptions:

  -- Only combustible liquid wastes (WCL) are fired through the main burner. Aqueous wastes (WNL) are injected through peripheral guns. Therefore, flame stabilization is assumed necessary if $(HV)_{WCL} < 8{,}000$ Btu/lb.

  -- Natural gas, rather than fuel oil, is burned for flame stabilization due to the wider turndown capabilities of auxiliary gas burners

  -- Low-fire fuel consumption is approximately 5 percent of liquid waste burner capacity. This percentage may range from zero up to 10 percent in actual practice.

  -- Elemental composition of natural gas (weight basis) is 69.3 percent carbon, 22.7 percent hydrogen, and 8.0 percent nitrogen

  -- Gross heating value of natural gas is approximately 21,800 Btu/lb, or 1,000 Btu/ft^3 at 60°F

- Working equations/decision criteria:

  -- If $(HV)_{WCL} \geq 8{,}000$ Btu/lb, set $F_{NG} = Q_{NG} = q_{NG} = 0$ and proceed to Section 3.4.3. If $(HV)_{WCL} < 8{,}000$ Btu/lb, see the following calculations.

  -- Gross heat input with natural gas:

$$Q_{NG} = 0.05\ (F_{WCL})\ (HV)_{WCL} = \underline{\hspace{3cm}}\ \text{Btu/hr}$$

  -- Volumetric flowrate of natural gas:

$$q_{NG} = Q_{NG}/1{,}000 = \underline{\hspace{3cm}}\ \text{scfh}$$

  -- Mass flowrate of natural gas:

$$F_{NG} = Q_{NG}/21{,}800 = \underline{\hspace{3cm}}\ \text{lb/hr}$$

3.4.3 Supplemental Fuel and Total Air Flow Requirements for Liquid Waste Incinerators

Supplemental fuel and combustion air requirements for liquid waste incinerators are determined by a series of material and energy balance calculations around a control volume consisting of both the ignition and combustion chambers. Sequential steps in the calculation procedure are:

1. Calculate the stoichiometric air requirement for liquid waste combustion and low-fire fuel (natural gas) combustion, if utilized.

2. Calculate the resulting combustion product flowrates.
3. Construct a heat balance around the ignition/combustion zones and calculate the overall excess air level which yields the desired combustion chamber outlet temperature, T_{I2}.
4. Compare this calculated excess air level to nominal minimum excess air requirements for liquid waste incinerators.
5. If necessary, based on step 4, calculate the supplemental fuel oil feedrate necessary to achieve the desired outlet temperature at an acceptable excess air level. This supplemental fuel oil feed is in addition to the low-fire flame stabilization fuel requirement.
6. Calculate the total air requirement.

Guidelines for performing these calculations are presented in the following sections.

3.4.3.1 Stoichiometric Air Requirements

- Purpose and limitations -- Stoichiometric air requirements must be calculated to provide the basis for subsequent excess air and total air calculations. Because the stoichiometric air calculations are based on standard combustion chemistry assumptions, little error is introduced.
- Applicability -- All liquid waste incinerators
- Assumptions -- Elemental waste and fuel components react with oxygen in air, oxygen present in the waste, or with each other in accordance with the following stoichiometry:
    - $C + O_2 = CO_2$
    - $1/2\ H_2 + Cl = HCl$
    - $H_2 + 1/2\ O_2 = H_2O$
    - $N_2 = N_2$
    - $H_2O = H_2O$
    - Metals = Ash (primarily oxides)
    - Formation of partial oxidation products of organic carbon (e.g., CO) is negligible compared to CO_2 formation
    - Organic hydrogen reacts preferentially with chlorine to form HCl, up to the point at which all organic chlorine is consumed

- Remaining hydrogen is oxidized to water vapor. Mole ratios of hydrogen-to-chlorine in the feed are greater than 1:1.

- Waste-bound oxygen contributes to the overall combustion oxygen demand

- Waste, fuel, and air nitrogen remain largely as diatomic nitrogen in the combustion gas

- Dissociation of ultimate oxidation products is negligible

- Oxygen demand for metallic ash oxidation is negligible

- Air composition on a mass basis is 76.8 percent nitrogen and 23.2 percent oxygen. Air moisture content is neglected due to its insignificant effects on the ensuing calculations.

- Natural gas composition on a mass basis is 69.3 percent carbon, 22.7 percent hydrogen, and 8 percent nitrogen as previously specified

- No. 2 fuel oil, which is used for supplemental heating if necessary, has a weight composition of 87.5 percent carbon, 12.5 percent hydrogen, negligible sulfur and nitrogen

- General relationships -- Stoichiometric oxygen requirements for various elemental waste components and fuels are presented in Table 15

TABLE 15. STOICHIOMETRIC OXYGEN REQUIREMENTS FOR COMBUSTION

Waste component	Stoichiometric oxygen requirements (lb/lb component)
C	2.664
H	7.936
O	-1.000
N	0
Cl	-0.226
H_2O	0
Ash	0
Natural gas	3.648
No. 2 fuel oil	3.323

- Working relationships:

  -- For the combined waste/low-fire natural gas feed, stoichiometric oxygen, air nitrogen, and air feedrates are:

$$(F_{O_2})_{stoich} = 2.664\ (F_C)_W + 7.936\ (F_{H_2})_W - (F_{O_2})_W$$

$$- 0.226\ (F_{Cl})_W + 3.648\ F_{NG} = \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

$$(F_{N_2})_{stoich} = 3.31\ (F_{O_2})_{stoich} = \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

$$(F_{air})_{stoich} = 4.31\ (F_{O_2})_{stoich} = \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

  -- If no. 2 fuel oil must be burned for supplemental heat (section 3.4.3.5), these expressions are modified in the following manner:

$$(F_{O_2})'_{stoich} = (F_{O_2})_{stoich} + 3.323\ F_{FO}, \text{ lb/hr}$$

$$(F_{N_2})'_{stoich} = 3.31\ (F_{O_2})'_{stoich}, \text{ lb/hr}$$

$$(F_{air})'_{stoich} = 4.31\ (F_{O_2})'_{stoich}, \text{ lb/hr}$$

3.4.3.2 Combustion Product Flowrates From Stoichiometric Combustion

- Purpose and limitations -- These calculations must be performed to provide a basis for the sensible and latent heat demand calculations outlined in section 3.4.3.3. Because the following calculations are based on standard combustion chemistry, little error is introduced by calculational methods in this section.

- Applicability -- All liquid waste incinerators

- Assumptions -- See Section 3.4.3.1 for general stoichiometry assumptions

- General relationships -- Based on the assumed combustion stoichiometry, combustion gas yields for various elemental waste components and fuels are shown in Table 16

- Working relationships:

  -- The mass flowrates of CO_2, H_2O, HCl, and ash in the incinerator exit gas are the same for stoichiometric and excess air operation. For the combined waste/low-fire natural gas feed, these mass flowrates are:

$$(F_{CO_2})_I = 3.664\ (F_C)_W + 2.539\ F_{NG} = \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

$$(F_{H_2O})_I = 8.936\ (F_{H_2})_W - 0.254\ (F_{Cl})_W + (F_{H_2O})_W + 2.028\ F_{NG}$$

$$= \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

TABLE 16. STOICHIOMETRIC YIELD OF WASTE COMBUSTION PRODUCTS, BY COMPONENT

Waste component	Stoichiometric yield (lb/lb component)				
	CO_2	H_2O	N_2[a]	HCl	Ash
C	3.664	0	0	0	0
H	0	8.936	0	0	0
O	0	0	0	0	0
N	0	0	1.0	0	0
Cl	0	-0.254	0	1.028	0
H_2O	0	1.0	0	0	0
Ash	0	0	0	0	1.0
Natural gas	2.539	2.028	0.08	0	0
No. 2 fuel oil	3.206	1.117	0	0	0

[a] Excludes nitrogen in combustion air

$(F_{HCl})_I = 1.028\ (F_{Cl})_W =$ __________ lb/hr

$(F_{ash})_I = (F_{ash})_{WL} =$ __________ lb/hr

-- Mass flowrates of oxygen and nitrogen in the incinerator exit gas and the total air feedrate depend on the amount of excess air used. General expressions for these mass flowrates for the combined waste/low-fire natural gas feed are:

$$(F_{O_2})_I = (F_{O_2})_{stoich}\ (EA),\ \text{lb/hr}$$

$$(F_{N_2})_I = (F_{N_2})_{stoich}\ (1 + EA) + (F_{N_2})_W + 0.08\ F_{NG},\ \text{lb/hr}$$

$$(F_{air})_I = (F_{air})_{stoich}\ (1 + EA),\ \text{lb/hr}$$

where EA is the fractional excess air level (percent excess air/100)

-- If no. 2 fuel oil must be burned for supplemental heat, the above expressions are modified for use in Section 3.4.3.5 in the following manner:

$$(F_{CO_2})'_I = (F_{CO_2})_I + 3.206\ F_{FO},\ \text{lb/hr}$$

$$(F_{H_2O})'_I = (F_{H_2O})_I + 1.117\ F_{FO},\ \text{lb/hr}$$

$$(F_{HCl})'_I = (F_{HCl})_I, \text{ lb/hr}$$

$$(F_{ash})'_I = (F_{ash})_I, \text{ lb/hr}$$

$$(F_{O_2})'_I = (F_{O_2})'_{stoich} (EA'), \text{ lb/hr}$$

$$(F_{N_2})'_I = (F_{N_2})'_{stoich} (1 + EA') + (F_{N_2})_W + 0.08 F_{NG}, \text{ lb/hr}$$

$$(F_{air})'_I = (F_{air})'_{stoich} (1 + EA'), \text{ lb/hr}$$

where EA' is the minimum excess air fraction defined in Section 2 and discussed in Section 3.4.3.4.

3.4.3.3 Calculated Excess Air at Specified Temperature

- Purpose and limitation -- The following energy balance calculations determine how much, if any, fuel oil must be burned to provide supplemental heat input. These calculations should be representative for most facilities, although the assumptions governing radiation heat loss and air preheating listed below may not be valid in all cases.

- Applicability -- All liquid waste incinerators

- Assumptions:

  -- The selected thermodynamic pathway for the heat balance calculation is as follows:

    1. Waste, fuel, and air enter at standard conditions of 60°F and 1 atm.

    2. Reaction occurs isothermally at 60°F.

    3. Water of combustion and free water in the waste are converted from liquid to vapor phase at 60°F.

    4. Combustion gas temperature adiabatically increases from 60°F to T_{I2}, the specified outlet temperature.

  -- No air preheating is employed

  -- Minute impacts of moisture in the combustion air are neglected

  -- Energy required to heat ash from 60°F to exit gas temperature is negligible, as is ash fusion energy

  -- Radiation heat loss is approximately 5 percent of the heat released by combustion

- Latent heat of evaporation of water, λ, at 60°F is 1,059.9 Btu/lb
- Combustion gases behave ideally over the applicable temperature range
- Mean heat capacities of combustion gas components between 60°F and typical gas exit gas temperatures do not differ significantly for the exit gas temperature range of 1,400° to 2,400°F. Therefore, mean heat capacities are specified for a 2,000°F exit gas temperature in Table 17.

- General relationships:
  - The general heat balance expression is: (Gross heat input with waste/low-fire fuel) = (Latent heat of evaporation of water at 60°F) + (Sensible heat required to raise gas temperature from 60°F to T_{I2}) + (Radiation heat losses), all terms in Btu/hr
  - The gross heat input term is:

    $$Q_I = Q_W + Q_{NG}, \text{ Btu/hr, or}$$

    $$Q'_I = Q_I + Q_{FO}, \text{ Btu/hr}$$

    if fuel oil must be burned for supplemental heating
  - The 5 percent radiation heat loss term is accounted for by multiplying Q_I (or Q'_I) by 0.95
  - Latent heat demand for water evaporation is expressed as $(F_{H_2O})_I\lambda$, Btu/hr, where λ is the latent heat of vaporization

TABLE 17. MEAN HEAT CAPACITIES OF COMBUSTION GAS COMPONENTS BETWEEN 60° AND 2,000°F

Gas component	Mean heat capacity ($\overline{c}_p$, Btu/lb°F)
CO_2	0.25
H_2O	0.52
O_2	0.24
N_2	0.27
HCl	0.21

in Btu/lb. Again, the $(F_{H_2O})'_I$ value is substituted if supplemental fuel oil is burned

-- Sensible heat demand is expressed as:

$$\sum (F_i)_I (\overline{C}_p)_i (T_{I2} - 60), \text{ Btu/hr}$$

where subscript i refers to the ith gas component

- Working relationships -- For combined waste/low-fire natural gas combustion, the integrated form of the heat balance expression is:

$$\begin{aligned} 0.95 (Q_W + Q_{NG}) = {} & 1{,}059.9 (F_{H_2O})_I + 0.25 (F_{CO_2})_I (T_{I2} - 60) \\ & + 0.52 (F_{H_2O})_I (T_{I2} - 60) \\ & + 0.21 (F_{HCl})_I (T_{I2} - 60) \\ & + 0.24 (F_{O_2})_{stoich} (EA) (T_{I2} - 60) \\ & + 0.27 [(F_{N_2})_{stoich} (1 + EA) + (F_{N_2})_W \\ & \qquad + 0.08 F_{NG}] (T_{I2} - 60), \end{aligned}$$

in which EA is the only unspecified variable.

Rearranging and simplifying, the expression for EA as a function of heat input, operating temperature and sensible/latent heat demand in liquid injection incinerators is:

$$EA = \frac{\dfrac{0.95 (Q_W + Q_{NG}) - 1{,}059.9 (F_{H_2O})_I}{(T_{I2} - 60)} - 0.25 (F_{CO_2})_I - 0.52 (F_{H_2O})_I - 0.21 (F_{HCl})_I - 0.27 [(F_{N_2})_{stoich} + (F_{N_2})_W + 0.08 F_{NG}]}{0.24 (F_{O_2})_{stoich} + 0.27 (F_{N_2})_{stoich}} \quad (1)$$

= ______________________________

3.4.3.4 Calculated Versus Minimum Excess Air Level Comparison

- Purpose and limitations:

  -- In all liquid waste incinerators, certain minimum excess air levels must be maintained to ensure complete oxidation of organic materials. Once these minimum levels have been established, they can be compared with the excess air level calculated in Section 3.4.3.3 to determine if this excess air level is acceptable. If the calculated level is less than minimum specifications, then auxiliary fuel firing will be needed to achieve the desired operating temperature, T_{I2}.

-- This section presents guidelines for minimum excess air level specification. These guidelines are necessarily approximate because actual excess air requirements depend on a number of factors including burner mixing characteristics, secondary air and gas flow patterns, and waste heterogeneity. However, these guidelines do represent current industry practice, so their application should not introduce major errors into the O&M cost evaluation.

- Applicability -- All liquid waste incinerators
- Assumptions:

  -- Minimum excess air requirements for liquid waste incinerators range from 25 to 50 percent

  -- The lower bound applies for high efficiency, high heat release rate burners, cyclonic or vortex flow designs, and relatively homogeneous wastes

  -- The upper bound applies for lower heat release rate, less efficient designs burning one or more heterogeneous waste streams

  -- Based on these guidelines, the minimum excess air requirement should be specified as $EA' = 0.25$ or $EA' = 0.5$ in the input data specifications, Section 2

- Decision criteria:

  -- If calculated EA is $<EA'$, proceed to Section 3.4.3.5 for auxiliary fuel feedrate calculations

  -- If calculated EA is $\geq EA'$, set $F_{FO} = 0$ and proceed to Section 3.4.3.6

3.4.3.5 Fuel Oil Feedrate Requirements for Supplemental Heating

- Purpose and limitations -- The following heat balance calculations are designed to estimate the fuel oil feedrate required to achieve the specified T_{I2} value at the acceptable minimum excess air level, EA'. The accuracy of these calculations is subject to the validity of the assumptions outlined in Sections 3.4.3.1 through 3.4.3.4.

- Applicability -- Subject to the decision criteria in Section 3.4.3.4

- Assumptions:

  -- No. 2 fuel oil with a higher heating value of 19,400 Btu/lb is used for supplemental heating purposes

  -- The low-fire natural gas feedrate for flame stabilization is maintained when supplemental heating fuel is burned. In actual practice, dual-liquid burners for waste and oil would normally be used and no natural gas would be burned in this situation. The fuel oil would serve the dual purposes of flame stabilization and supplemental heat input. From a heat balance standpoint, however, the trade-off is merely Btu's of fuel oil versus Btu's of natural gas in the gross heat input term. This trade-off will not affect the total fuel cost significantly, therefore, complete reconstruction of the material and energy balances established to this point is unwarranted.

  -- See Sections 3.4.3.1 through 3.4.3.4 for additional assumptions

- General relationships -- The general heat balance concept used here is the same as that presented in Section 3.4.3.3. The only differences are:

  - An additional heat input term, 19,400 F_{FO}, Btu/hr, is added to account for fuel oil firing

  - $(F_i)'_I$ rather than $(F_i)_I$ relationships are used in the sensible and latent heat terms, where i refers to the ith combustion gas component

  - $(F_{O_2})'_{stoich}$ and $(F_{N_2})'_{stoich}$ relationships are used

  - EA', specified as 0.25 or 0.50, is used rather than the dependent variable, EA

- Working relationships:

  -- The restructured heat balance equation is (all terms in Btu/hr):

$$0.95\ (Q_W + Q_{NG} + 19{,}400\ F_{FO}) = 1{,}059.9\ [(F_{H_2O})_I + 1.117\ F_{FO}]$$

$$+\ 0.25\ [(F_{CO_2})_I + 3.206\ F_{FO}]\ (T_{I2} - 60) + 0.52\ [(F_{H_2O})_I$$

$$+\ 1.117\ F_{FO}]\ (T_{I2} - 60) + 0.21\ (F_{HCl})_I\ (T_{I2} - 60)$$

$$+\ 0.24\ [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (EA')\ (T_{I2} - 60)$$

$$+ 0.27 \left([(F_{N_2})_{stoich} + 11\ F_{FO}]\ (1 + EA') + (F_{N_2})_W + 0.08\ F_{NG} \right) (T_{I2} - 60)$$

-- In this expression, F_{FO} is the only unknown. Rearranging and simplifying terms, the expression for F_{FO} in lb/hr as a function of waste heat input, operating temperature, and excess air for liquid injection incinerators, is:

$$F_{FO} = \frac{1{,}059.9\ (F_{H_2O})_I - 0.95\ (Q_W + Q_{NG}) + \left| 0.25\ (F_{CO_2})_I + 0.52\ (F_{H_2O})_I + 0.21\ (F_{HCl})_I + 0.27\ [(F_{N_2})_{stoich} + (F_{N_2})_W + 0.08\ F_{NG}] + [0.24\ (F_{O_2})_{stoich} + 0.27\ (F_{N_2})_{stoich}]\ (EA') \right| (T_{I2} - 60)}{17{,}246 - (4.353 + 3.768\ EA')\ (T_{I2} - 60)} \tag{2}$$

= ______________________ lb/hr

3.4.3.6 Total Air Flow Requirements

- Purpose and limitations -- The total combustion air requirement must be calculated to determine combustion air blower power requirements in a subsequent section of this report. The accuracy of the total air flow calculations is subject to the validity of the assumptions outlined in the preceding subsections.
- Applicability -- All liquid waste incinerators
- Working relationships:

-- If the EA value calculated in Section 3.4.3.3 exceeds the minimum requirements and F_{FO} = 0, the total air feed is:

$(F_{air})_I = (F_{air})_{stoich}\ (1 + EA)$ = ___________ lb/hr

For utilization in subsequent sections, also calculate:

$(F_{O_2})_I = (F_{O_2})_{stoich}\ (EA)$ = ___________ lb/hr

$(F_{N_2})_I = (F_{N_2})_{stoich}\ (1 + EA) + (F_{N_2})_W + 0.08\ F_{NG}$

= ___________ lb/hr

-- If $F_{FO} > 0$, the total air feedrate expression is:

$(F_{air})'_I = 4.31\ [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (1 + EA')$

= ___________ lb/hr

For utilization in subsequent sections, also calculate:

$$(F_{CO_2})'_I = (F_{CO_2})_I + 3.206\ F_{FO}$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{H_2O})'_I = (F_{H_2O})_I + 1.117\ F_{FO}$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{HCl})'_I = (F_{HCl})_I = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{ash})'_I = (F_{ash})_I = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{O_2})'_I = [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (EA')$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{N_2})'_I = 3.31\ [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (1 + EA')$$

$$+ (F_{N_2})_W + 0.08\ F_{NG} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

3.4.4 Supplemental Fuel and Total Air Flow Requirements for Solid and Liquid Waste Incinerators

Supplemental fuel and combustion air requirements for incinerators burning solid and liquid wastes are more difficult to determine quantitatively than fuel and/or air requirements for liquid waste incinerators. In liquid waste incinerators, ignition is ensured by proper burner management, so the overall energy balance can be constructed assuming (with negligible error) that 100 percent of the heat of combustion of incoming waste will be released. This is the approach used in Section 3.4.3 to predict fuel and air requirements.

In incinerators burning both solids and liquids, it is also safe to assume 100 percent release of the heat of combustion of incoming liquid wastes. However, it is not always valid to make the same assumption for incoming solids due to localized gas temperature depression and ignition problems associated with high moisture content solids. If localized ignition problems are encountered, the overall energy balance approach used for liquid waste incinerators will underestimate the actual fuel requirements for incinerators burning both liquids and solids.

Two approaches may be used to estimate the actual fuel requirements for incinerators burning solids as well as liquids. The first, and most direct method is to perform a zonal heat balance calculation to determine the fuel firing rate necessary to ensure the ignition of solid wastes. Unfortunately, this approach requires knowledge of the ignition characteristics of the waste(s) in question as well as detailed modeling of heat and mass transfer rates in various kiln or hearth regimes. These calculations are beyond the scope of the present study.

The second approach is a modification of the overall energy balance approach used for liquid waste incinerators, in which rules of thumb concerning the impacts of waste moisture content on supplemental heating requirements are adopted. One such rule of thumb is that rotary kiln incinerators can handle only about 50 percent of the waste moisture content that would be predicted by overall energy balance calculations without experiencing ignition problems.

Assuming that this rule of thumb is reasonably valid for hearth incinerators as well as rotary kilns, supplemental fuel and combustion air requirements for these incinerators can be estimated by the following approach:

1. Calculate supplemental fuel requirements by the methods presented in Section 3.4.3, assuming (1) a hypothetical free moisture feedrate two times the actual free moisture feedrate, and (2) minimum excess air levels typical of rotary kiln and hearth incinerator operation rather than the minimum excess air levels discussed in Section 3.4.3.4 for liquid waste incinerators.

2. Based on this calculated fuel feedrate, determine the total excess air level which satisfies the overall energy balance expression. The actual free moisture feedrate is used in this calculation. If the calculated fuel requirement is zero in step 1, then the methods presented in Section 3.4.3.3 are used to calculate the excess air level which satisfies the overall energy balance.

3. Based on the excess air level calculated in step 2, determine the total air flow requirement.

Guidelines to perform these calculations are presented in the following sections.

3.4.4.1 Supplemental Fuel Requirements

- Purpose and limitations -- The following calculations are designed to estimate fuel oil feed requirements for rotary kiln and hearth incinerators burning solid wastes only or solid and liquid wastes. These fuel requirements include supplemental heating requirements to achieve the design afterburner exit gas temperature (T_{I2}), plus an extra allowance to ensure that solid waste ignition is achieved in the primary chamber. The calculations are not rigorous because rules of thumb, rather than analytical methods, are used to estimate the additional fuel requirements for ignition. However, the results should be accurate enough for the purposes of this study.

- Applicability -- All rotary kiln and hearth incinerators

- Assumptions:

  -- When the overall energy balance approach outlined in Section 3.4.3 is applied to solid waste incinerators, there is a tendency to underestimate the supplemental fuel requirements because this approach does not account for localized ignition problems in the primary chamber

  -- The additional supplemental fuel requirement to ensure solid waste ignition is directly related to the free moisture content of the waste feed

  -- Rotary kilns can handle only about 50 percent of the free water that would be anticipated from an overall energy balance calculation without experiencing ignition problems. The reciprocal of this rule-of-thumb is that 1 lb of free water has the same impact on ignition in the primary chamber as 2 lb of free water in the overall energy balance calculation.

  -- Minimum excess air requirements for rotary kiln systems are approximately 100 percent if only bulk solids are burned, and 150 percent if containerized wastes are burned (large kilns only). Thus, EA' is either 1.0 or 1.5 for kiln systems. The appropriate value should be entered in Section 2.

  -- Minimum excess air requirements for hearth incinerators are more difficult to generalize because primary chamber operation may be substoichiometric, stoichiometric, or oxygen rich. For controlled-air-type (substoichiometric primary chamber) units overall excess air usage is approximately 150 percent. For multiple chamber types (oxidizing primary chamber), overall excess air usage is approximately 200 percent. Therefore, EA' is 1.5 to 2.0 for hearth incinerators. Again, the appropriate value should be entered in Section 2.

  -- Other assumptions relating to combustion stoichiometry, radiation heat loss, latent heat demand, and sensible heat loss are the same as those listed in Section 3.4.3.

- Working relationships:

  -- Based on the information presented in Section 3.4.3 and the foregoing assumptions, the following relationships apply:*

---

*$(F_i)'$ signifies supplemental fuel oil firing in addition to waste and low-fire natural gas combustion.

$$(F_{O_2})_{stoich} = 2.664\ (F_C)_W + 7.936\ (F_{H_2})_W - (F_{O_2})_W$$

$$- 0.226\ (F_{Cl})_W + 3.648\ F_{NG}$$

$$= \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{O_2})'_{stoich} = (F_{O_2})_{stoich} + 3.323\ F_{FO}, \text{ lb/hr}$$

$$(F_{N_2})_{stoich} = 3.31\ (F_{O_2})_{stoich} = \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{N_2})'_{stoich} = 3.31\ (F_{O_2})'_{stoich}, \text{ lb/hr}$$

$$(F_{air})_{stoich} = 4.31\ (F_{O_2})_{stoich} = \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{air})'_{stoich} = 4.31\ (F_{O_2})'_{stoich}, \text{ lb/hr}$$

$$(F_{CO_2})_I = 3.664\ (F_C)_W + 2.539\ F_{NG} = \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{CO_2})'_I = (F_{CO_2})_I + 3.206\ F_{FO}, \text{ lb/hr}$$

$$(F_{HCl})_I = (F_{HCl})'_I = 1.028\ (F_{Cl})_W = \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{O_2})_I = (F_{O_2})_{stoich}\ (EA), \text{ lb/hr}$$

$$(F_{O_2})'_I = (F_{O_2})'_{stoich}\ (EA'), \text{ lb/hr}$$

$$(F_{N_2})_I = (F_{N_2})_{stoich}\ (1 + EA) + (F_{N_2})_W + 0.08\ F_{NG}, \text{ lb/hr}$$

$$(F_{N_2})'_I = (F_{N_2})'_{stoich}\ (1 + EA') + (F_{N_2})_W + 0.08\ F_{NG}, \text{ lb/hr}$$

$$(F_{air})_I = 4.31\ (F_{O_2})_{stoich}\ (1 + EA), \text{ lb/hr}$$

$$(F_{air})'_I = 4.31\ (F_{O_2})'_{stoich}\ (1 + EA'), \text{ lb/hr}$$

$$(F_{H_2O})_I = 8.936\ (F_{H_2})_W - 0.254\ (F_{Cl})_W + (F_{H_2O})_W + 2.028\ F_{NG}$$

$$= \underline{\qquad\qquad\qquad} \text{ lb/hr}$$

$$(F_{H_2O})'_I = (F_{H_2O})_I + 1.117\ F_{FO}, \text{ lb/hr}$$

$$(F_{H_2O})''_I = (F_{H_2O})'_I + (F_{H_2O})_W, \text{ lb/hr}$$

where the latter expression is an artificial water vapor flowrate used in estimating the additional heat input requirement to achieve ignition of feed solids.

-- Substituting the appropriate expressions into Equation 2, simplifying, and solving for F_{FO} yields:

$$F_{FO} = \frac{1{,}059.9\,[(F_{H_2O})_I + (F_{H_2O})_W] - 0.95\,(Q_W + Q_{NG}) + \Big[0.25\,(F_{CO_2})_I + 0.52\,[(F_{H_2O})_I + (F_{H_2O})_W] + 0.21\,(F_{HCl})_I + 0.27\,[(F_{N_2})_{stoich} + (F_{N_2})_W + 0.08\,F_{NG}] + [0.24\,(F_{O_2})_{stoich} + 0.27\,(F_{N_2})_{stoich}]\,(EA')\Big]\,(T_{I2} - 60)}{17{,}246 - (4.353 + 3.768\,EA')\,(T_{I2} - 60)} \tag{3}$$

$= \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$ lb/hr

3.4.4.2 Calculated Excess Air at a Specified Temperature

- Purpose and limitations:

-- The following procedures are designed to estimate the excess air level for the system (primary chamber plus afterburner) needed to satisfy the overall energy balance expression and provide thermodynamic consistency. The calculations employed depend on the results of the fuel feedrate calculation in the preceding subsection.

-- If the calculated fuel feedrate, $F_{FO} \leq 0$ then no supplemental fuel firing is required. In this case, Equation 3-1 in Section 3.4.3.3 can be used without modification to calculate EA, which will be greater than the minimum excess air value, EA', used in Section 3.4.4.1. This is the simplest case, with no limitations in accuracy over and above those discussed in Section 3.4.3. If the calculated fuel feedrate, $F_{FO} > 0$, however, a different approach must be used to estimate the total excess air level for the system.

-- The fuel oil feedrate, F_{FO}, calculated in the preceding section is somewhat higher than the feedrate that would be calculated using the standard energy balance approach outlined in Section 3.4.3 because additional heat input requirements to ensure solid waste ignition are taken into account. These additional heat input requirements are determined by artificially doubling the free moisture feedrate, $(F_{H_2O})_W$, pounds per hour, in the sensible and latent heat demand terms of the energy balance.

-- Once the required fuel oil feedrate is determined, however, the overall energy balance for the system (primary chamber plus afterburner) must still be satisfied for thermodynamic consistency. Because the actual free moisture feedrate is half of that used in the fuel oil feedrate calculation, the total latent and sensible heat demand for the system is less than that indicated in the fuel feedrate calculation. Therefore, disregarding the spatial considerations involved in achieving solid waste ignition, the total excess air level for the primary chamber and afterburner system will be somewhat higher than the minimum EA' value used to calculate fuel oil feed requirements. The following calculations are designed to estimate the EA" value that satisfies the overall energy balance and provides thermodynamic consistency. The accuracy of these calculations is commensurate with the accuracy of the fuel feedrate calculations.

- Applicability -- All rotary kiln and hearth incinerators
- Assumptions -- No additional assumptions are introduced in this section
- General relationships:
  - In the case where $F_{FO} < 0$, the excess air level, EA, is calculated using Equation 1 in Section 3.4.3.3.
  - In the case where $F_{FO} > 0$, modification of the sensible and latent heat demand terms involves the following relationships:

    (Sensible + latent heat demand of hypothetical free moisture)

    = (Sensible heat demand of additional excess air)
  - In mathematical terms, this relationship is:

$$1{,}059.9\ (F_{H_2O})_W + 0.52\ (F_{H_2O})_W\ (T_{I2} - 60) = 0.24\ (F_{O_2})_{add}$$

$$(T_{I2} - 60) + 0.27\ (3.31)\ (F_{O_2})_{add}\ (T_{I2} - 60)$$

where $(F_{O_2})_{add}$ is pounds per hour of oxygen in the additional air.

- Working relationships:
  - Based on the foregoing relationship:

$$(F_{O_2})_{add} = \frac{[1{,}059.9 + 0.52\ (T_{I2} - 60)](F_{H_2O})_W}{1.13\ (T_{I2} - 60)}$$

$$= \_\_\_\_\_\_\_\_\_\_\ \text{lb/hr}$$

  - The total excess air level, EA", is then given by:

$$EA'' = \frac{[(F_{O_2})_{stoich} + 3.323\ F_{FO}](EA') + (F_{O_2})_{add}}{(F_{O_2})_{stoich} + 3.323\ F_{FO}}$$

$$= \_\_\_\_\_\_\_\_\_\_\_\_$$

3.4.4.3 Total Air Flow Requirements

- Purpose and limitations -- The total combustion air requirement must be calculated to determine combustion air blower power requirements in a subsequent section of this report. The accuracy of the total air flow calculation is subject to the validity of the assumptions used in the preceding subsections.
- Applicability -- All rotary kiln and hearth incinerators
- Working relationships:

-- For the case where $F_{FO} \leq 0$ in Section 3.4.4.1 the total air feedrate is:

$$(F_{air})_I = 4.31\ (F_{O_2})_{stoich}\ (1 + EA) = \underline{\hspace{3cm}}\ \text{lb/hr}$$

For use in subsequent sections, also calculate:

$$(F_{O_2})_I = (F_{O_2})_{stoich}\ (EA) = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{N_2})_I = (F_{N_2})_{stoich}\ (1 + EA) + (F_{N_2})_W + 0.08\ F_{NG}$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

-- For the case where $F_{FO} > 0$, the total air feedrate is:

$$(F_{air})'_I = 4.31\ [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (1 + EA")$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

For use in subsequent sections, also calculate:

$$(F_{O_2})'_I = [(F_{O_2})_{stoich} + 3.323\ F_{FO}]\ (EA")$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{N_2})'_I = [(F_{N_2})_{stoich} + 11\ F_{FO})]\ (1 + EA") + (F_{N_2})_W$$

$$+ 0.08\ F_{NG} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{CO_2})'_I = (F_{CO_2})_I + 3.206\ F_{FO} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{H_2O})'_I = (F_{H_2O})_I + 1.117\ F_{FO} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$(F_{HCl})'_I = (F_{HCl})_I = \underline{\hspace{3cm}}\ \text{lb/hr}$$

3.4.5 Supplemental Heating Fuel Oil Feed Pump Power Requirements

- Purpose and limitations -- This section provides a method of estimating the power requirements for fuel oil feed pump operation. The accuracy of this method is subject to the accuracy of the fuel oil feed requirements determined in Section 3.4.3 or 3.4.4, and the applicability of the assumptions listed below for specific facilities in question. A high degree of accuracy is unnecessary for the purposes of this study because the power requirements for fuel oil feed pump operation are small compared to other system power requirements

- Applicability -- All incinerators burning no. 2 fuel oil for supplemental heating purposes

- Assumptions:

  -- 10:1 recycle ratio on all fuel delivery lines to maintain constant nozzle pressure on turndown

  -- Pump discharge pressure is 100 psig. In practice, the required discharge pressure will vary depending on the atomization technique employed and line pressure drop, which is a function of site-specific logistics.

  -- No. 2 fuel oil density is 53 lb/ft^3, equivalent to a specific gravity of 0.85 at 60°F

  -- Overall pump/motor efficiency is 40 percent

- General relationship -- The pump power requirement is given by the general expression:

$$\text{Power, hp} = 7.27 \times 10^{-5} \frac{(\text{Flowrate, lb/hr})(\text{Discharge pressure, psig})}{(\text{Density, lb/ft}^3)(\text{Fractional efficiency})}$$

- Working relationship -- Based on the assumptions listed above, pump power is related to the required fuel oil feedrate, F_{FO}, by:

$$(P_{pump})_{FO} = 3.43 \times 10^{-3} F_{FO} = \underline{\hspace{4cm}} \text{ hp}$$

3.4.6 Combustion Air Blower Power Requirements

- Purpose and limitations -- This section presents guidelines to estimate the power requirements for combustion air blower operation. The accuracy of the calculations is contingent upon (1) the accuracy of the total air flow calculation in Section 3.4.3 or 3.4.4, (2) the accuracy of the atomizing air flow calculation in Section 3.3.7, and (3) the applicability of the assumptions listed below to specific cases.

- Applicability -- All facilities
- Assumptions:

  -- All cooling and combustion air, excluding atomizing air, is supplied to the incinerator via one or more forced-draft blowers. This assumption is somewhat conservative for certain designs, particularly rotary kiln incinerators in which a variable fraction of the combustion air flow is induced through negative pressure operation. However, the alternative is case-by-case design evaluation which is beyond the scope of this study.

  -- All system designs include ID fans, so high blower delivery pressures are not required to create draft through the air pollution control system. Blower discharge pressures are nominally 20 in. W.C.

  -- Inlet air is at 60°F and 14.7 psia with a specific volume of 13.09 ft^3/lb

  -- Overall blower/motor efficiency is 50 percent

- General relationships -- Power requirements are given by:

$$\text{Power, hp} = \frac{1.57 \times 10^{-4}\ (\text{Volumetric flow, CFM})(\text{Developed head, in W.C.})}{(\text{Fractional blower/motor efficiency})}$$

- Working relationships:

  -- Combustion air requirements are calculated from the total air requirement and the atomizing air requirement as follows:

$$(F_{air})_{bl} = [(F_{air})_I, \text{ or } (F_{air})'_I] - (F_{air})_{comp}$$

$$= \_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ lb/hr}$$

$$(q_{air})_{bl} = 0.218\ (F_{air})_{bl} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{scfm}$$

  -- Based on the assumptions listed above, motor horsepower requirements are related to $(q_{air})_{bl}$ by:

$$P_{bl} = 6.28 \times 10^{-3}\ (q_{air})_{bl} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{ hp}$$

3.4.7 Combustion Gas Flow and Composition

- Purpose and limitations -- The composition and flow of combustion gas leaving the incinerator must be known to perform material and energy balance calculations on all downstream unit operations. The calculations needed to determine combustion gas component flowrates are already detailed in Sections 3.4.3 and 3.4.4. This section is intended only to summarize the results of those calculations into a usable format for subsequent manipulation.

- Applicability -- All facilities
- Assumptions -- Standard conditions of temperature and pressure are 60°F and 14.7 psia
- Working relationships:

-- Gas component volumetric flowrates are given by:

$$q_{CO_2} = 0.144\ [(F_{CO_2})_I \text{ or } (F_{CO_2})'_I]$$

$= \underline{\hspace{4cm}}$ scfm

$$q_{O_2} = 0.198\ [(F_{O_2})_I \text{ or } (F_{O_2})'_I]$$

$= \underline{\hspace{4cm}}$ scfm

$$q_{N_2} = 0.226\ [(F_{N_2})_I \text{ or } (F_{N_2})'_I]$$

$= \underline{\hspace{4cm}}$ scfm

$$(q_{HCl})_I = 0.174\ [(F_{HCl})_I \text{ or } (F_{HCl})'_I]$$

$= \underline{\hspace{4cm}}$ scfm

$$(q_{H_2O})_I = 0.352\ [(F_{H_2O})_I \text{ or } (F_{H_2O})'_I]$$

$= \underline{\hspace{4cm}}$ scfm

-- The dry gas flowrate (assumed constant throughout downstream operations) is given by:

$$F_{DG} = (F_{CO_2})_I + (F_{O_2})_I + (F_{N_2})_I, \text{ or } (F_{CO_2})'_I + \text{, etc.}$$

$= \underline{\hspace{4cm}}$ lb/hr

$$q_{DG} = q_{CO_2} + q_{O_2} + q_{N_2} = \underline{\hspace{4cm}} \text{ scfm}$$

-- The dry gas molecular weight is given by:

$$(MW)_{DG} = \frac{44\ q_{CO_2} + 32\ q_{O_2} + 28\ q_{N_2}}{q_{DG}} = \underline{\hspace{4cm}}$$

-- The total gas flowrate leaving the incinerator is given by:

$$(q_{TG})_I = q_{DG} + (q_{HCl})_I + (q_{H_2O})_I = \underline{\hspace{3cm}} \text{ scfm}$$

$$(F_{TG})_I = F_{DG} + (F_{H_2O})_I + (F_{HCl})_I = \underline{\hspace{3cm}} \text{ lb/hr}$$

3.4.8 Particulate Loading in Combustion Gases

- Purpose and limitations -- This section presents methods to estimate particulate loadings in liquid waste incinerator effluents, and roughly estimate particulate loadings in rotary kiln and hearth incinerator effluents

- Applicability -- All facilities

- Assumptions:

  -- 100 percent of the ash contained in liquid wastes is carried over as particulate in the incinerator exit gas. This applies to all incinerator types in which liquid wastes are burned.

  -- In rotary kiln incinerators, 25 percent of the ash contained in slurries and solid wastes is carried over as particulate. This is a rough approximation which will vary with numerous kiln design and operating practices.

  -- In hearth-type incinerators, particulate carryover may range from 5 to 25 percent of the ash contained in solid wastes. The lower percentage is roughly applicable for designs which employ gentle (or no) charge stoking, while the higher percentage is roughly applicable for traveling grate designs with substantial underfire air.

  -- Good fixed carbon burnout is achieved, so little carbonaceous material is present as flyash

- Working relationships:

  -- For liquid waste incinerators, the particulate loading in the incinerator exit gas is given by:

$$(C_{part})_I = 117\,\frac{(F_{ash})_{WL}}{q_{DG}} = \underline{\hspace{4cm}} \text{ gr/dscf}$$

  -- For rotary kiln incinerators and hearth-type incinerators with characteristically high particulate carryover rates (from Section 2):

$$(C_{part})_I = 117\,\frac{(F_{ash})_{WL} + 0.25\,(F_{ash})_{WS}}{q_{DG}} = \underline{\hspace{2cm}} \text{gr/dscf}$$

-- For hearth incinerators with characteristically low particulate carryover rates (see Section 2):

$$(C_{part})_I = 117 \frac{(F_{ash})_{WL} + 0.05\ (F_{ash})_{WS}}{q_{DG}} = \_\_\_\_\_\_\_\_ \text{gr/dscf}$$

3.4.9 Charge Stoking and Bottom Ash Handling Requirements

- Purpose and limitations

  -- This section provides estimates of the power required for kiln rotation and charge movement and ash removal in large hearth-type incinerators. While the connected horsepower estimates for kiln drives are considered reasonably accurate, the estimated power requirements for charge movement and ash removal in the larger hearth incinerators should be considered rough estimates. These power requirements are difficult to estimate with any real accuracy because a number of design alternatives are possible. However, a high degree of accuracy is unnecessary for the purposes of this study because the power requirements in question represent a small fraction of the total connected horsepower for facility operation.

  -- This section also presents methods to estimate water and power requirements for bottom ash handling in larger kiln and hearth incinerators. The accuracy of these methods for specific facilities is subject to the applicability of the assumptions listed below. However, a high degree of accuracy is unnecessary because ash handling costs are small compared to other O&M costs.

- Applicability -- Rotary kiln and hearth incinerator facilities

- Assumptions:

  -- Kilns are driven at rotational velocities ranging from 0.1 to 2 rpm by electric motors through gear reducers

  -- Solids charge movement and ash removal is achieved automatically in 10 to 50 million Btu/hr hearth incinerators via drag-flight conveyors, dumping grates, ram stokers, or hearth pulsation mechanisms

  -- In category A (1 to 10 million Btu/hr) kiln and hearth incinerator facilities, ash is manually removed from the collection pit and handled dry

  -- In larger kiln and hearth incinerator facilities, bottom ash is collected in a water quench tank and removed by submerged conveyor system. Net water consumption is 1 lb/lb ash, or 0.12 gal/lb ash.

  - The assumptions regarding flyash/bottom ash partitioning presented in the preceding section are applicable in this section as well
  - Ash quench water pump discharge pressure is nominally 30 psig
  - Overall pump/motor efficiency is 40 percent

- Working relationships:
  - For rotary kilns, connected drive horsepower versus capacity estimates are shown in Table 18
  - For 1 to 10 million Btu/hr hearth incinerators, $P_{drive} = 0$
  - For 10 to 50 million Btu/hr hearth incinerators, a rough estimate of stoker drive power is $P_{drive} = 3$ hp
  - For category A kilns and hearth incinerators, ash is handled manually in dry form, so:

$$q_{AW} = (P_{pump})_{AW} = (P_{conv})_{ash} = 0$$

  - For larger rotary kilns and the more violently agitated, category B hearth incinerator designs, the ash quench water flow and pumping power are given by:

$q_{AW} = 0.0015\ (F_{ash})_{WS} =$ _______________ gpm

$(P_{pump})_{AW} = 6.55 \times 10^{-5}\ (F_{ash})_{WS} =$ _____________ hp

TABLE 18. POWER REQUIREMENTS FOR KILN ROTATION

Incinerator capacity, Q_{Tmax} (million Btu/hr)	P_{drive} (hp)
<35	5
35 to 65	7.5
65 to 100	10

-- For more gently agitated, category B hearth incinerator designs:

$$q_{AW} = 0.0019\ (F_{ash})_{WS} = \_\_\_\_\_\_\_\_\_\_\_\_\ \text{gpm}$$

$$(P_{pump})_{AW} = 8.3 \times 10^{-5}\ (F_{ash})_{WS} = \_\_\_\_\_\_\_\_\_\_\_\_\ \text{hp}$$

-- In general, ash conveyor power requirements should not exceed $(P_{conv})_{ash} = 1$ hp for category B and C facilities

3.4.10 Startup Fuel Requirements

- Purpose and limitations -- This section is designed to estimate the quantities of fuel that must be burned to bring the incinerator up to the desired operating temperatures, T_{I1} in the primary chamber and T_{I2} in the secondary chamber. A number of design assumptions must be made to perform these startup fuel calculations, therefore, the results may not be specific for any given manufacturer's design. However, the results should be generally representative.

- Applicability -- All facilities

- Assumptions:

  -- Two distinctly different startup procedures are utilized in most hazardous waste incineration facilities, depending on whether or not new refractory has been installed during the downtime period

  -- If refractory curing is required, startup fuel burners are modulated up to full firing capacity very slowly to limit the rate of refractory heating to approximately 50°F/hr. Startup can require 2 to 3 days under these conditions.

  -- In most cases, however, the objective of startup is simply to heat the inner refractory surface to its design steady-state operating temperature before wastes are introduced to minimize wall quenching effects. Startup can be achieved in a matter of hours under these conditions. Because this is the most common startup mode, rapid fuel burner modulation up to full-firing capacity is assumed in the following discussion.

  -- The inner refractory surface temperature at the conclusion of startup is equivalent to the desired bulk gas temperature during steady-state operation, T_{I1} for primary chamber operation and T_{I2} for secondary chamber operation. This assumption is somewhat conservative because the film resistance to heat transfer from the bulk gas to the wall is ignored.

- -- Incinerator exit ducts are aligned perpendicular to the line of sight of the flame. Thus, all flame radiation is directed to the walls of the combustion chamber.

- -- No. 2 fuel oil with a higher heating value of 19,400 Btu/lb is used for startup

- -- Design heat release rates are 30,000 Btu/hr-ft^3 for liquid waste incinerators and rotary kilns, and 15,000 Btu/hr-ft^3 for hearth primary chambers during normal steady-state operation

- -- Design afterburner residence times for kiln and hearth incinerators are nominally 2 sec, based on the combustion gas flow at T_{I2}

- -- Liquid waste incinerators and afterburners are cylindrical with length (L) to internal diameter (D_i) ratios of 3:1

- -- Kiln length to internal diameter ratios are 2:1

- -- Hearth primary chambers are rectangular, with the following internal length (L_i), width (W_i), and height (H_i) ratio:

$$L_i = 2W_i = 2H_i$$

- General relationships:

  - -- The general procedure for estimating startup fuel requirements is as follows:

    1. Select a realistic startup time (t_{start}) for the incinerator as a whole (primary and secondary chambers). Recommended t_{start} values versus secondary chamber temperature (T_{I2}) are indicated in Table 19. Whether or not these values are used, the user should specify t_{start} in Section 2.

    2. Using Figure 13, identify the gross heat input fluxes, Q_{start}, Btu/hr-ft^2, corresponding to (1) t_{start} and T_{I1}, and (2) t_{start} and T_{I2}. Figure 13 allows for dry flue gas and moisture losses, as well as the heat for refractory heat storage and losses. The heat flux relationships shown here are independent of firebrick thickness, up to 6 hr startup time (Reference 3).

    3. Based on the combustion chamber geometric assumptions listed above, calculate internal surface areas for the primary chamber (A_{s1}) and the secondary chamber (A_{s2}).

TABLE 19. RECOMMENDED STARTUP TIME AS A FUNCTION OF SECONDARY CHAMBER TEMPERATURE

Secondary chamber (or liquid injector incinerator) temperature, T_{I2} (°F)	Recommended startup time, t_{start} (hr)
1,400	2.000
1,600	2.225
1,800	2.500
2,000	3.000
2,200	3.750
2,400	4.250

a. For liquid injection incinerators, there is no primary chamber, so:

$$V_i,\ ft^3 = \frac{Q_{Tmax}}{30,000}$$

and because $L_i = 3\ D_i$:

$$D_i,\ ft = \left(\frac{4\ V_i}{3\pi}\right)^{1/3}$$

Internal surface area (A_s) is thus:

$$A_s,\ ft^2 = 3\pi\ D_i{}^2$$

b. For rotary kilns (primary chamber):

$$V_{i1},\ ft^3 = \frac{Q_{Tmax}}{30,000}$$

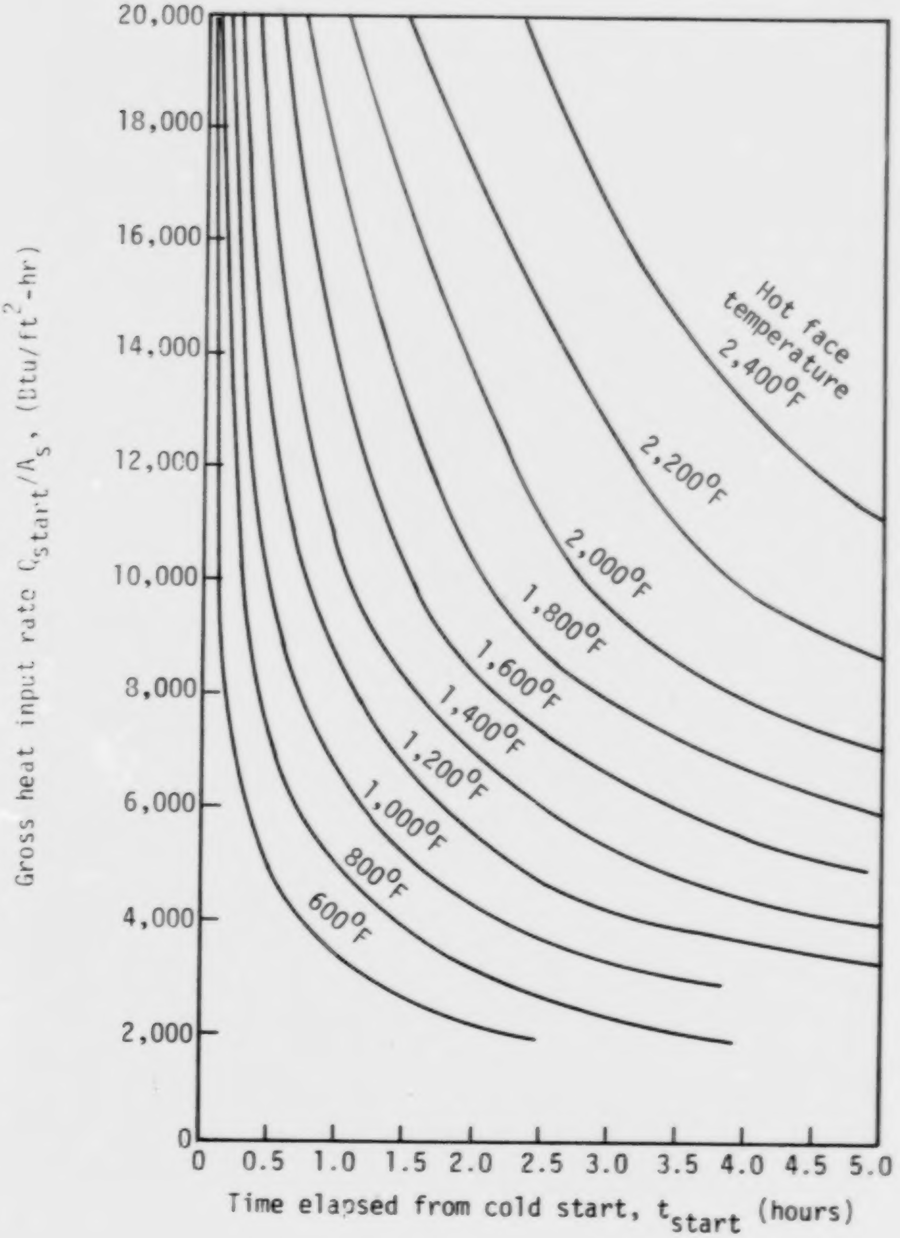


Figure 13. Time required for incinerator startup (Reference 3).

and $L_{i1} = 2\ D_{i1}$, so:

$$D_{i1},\ \text{ft} = \left(\frac{2V_{i1}}{\pi}\right)^{1/3}$$

and A_{s1}, $\text{ft}^2 = 2\pi\ D_{i1}{}^2$

c. For hearth incinerator primary chambers:

$$V_{i1},\ \text{ft}^3 = \frac{Q_{T\max}}{15{,}000}$$

$$W_{i1} = H_{i1} = 0.5\ L_{i1},\ \text{ft} = (0.5\ V_{i1})^{1/3}$$

and A_{s1}, $\text{ft}^2 = 10\ W_{i1}{}^2$

d. For kiln and hearth afterburner chambers:

$$V_{i2},\ \text{ft}^3 = 0.0333\ (qTG)I\left(\frac{T_{I2} + 460}{520}\right)$$

and because $L_i = 3\ D_i$:

$$D_{i2},\ \text{ft} = \left(\frac{4\ V_{i2}}{3\pi}\right)^{1/3}$$

and, A_{s2}, $\text{ft}^2 = 3\pi\ D_{i2}{}^2$

4. Multiply internal surface areas (A_{s1}) and (A_{s2}), ft^2, by heat fluxes, $(Q_{start}/A_s)_1$ and $(Q_{start}/A_s)_2$, to determine gross heat input requirements

$$Q_{start},\ \text{Btu/hr} = \left(\frac{Q_{start}}{A_s}\right)_1 A_{s1} + \left(\frac{Q_{start}}{A_s}\right)_2 A_{s2}$$

5. Calculate startup heat requirements in terms of no. 2 fuel oil consumption:

$$(F_{FO})_{start},\ \text{lb/hr} = \left(\frac{Q_{start}}{19{,}400}\right)$$

$$(M_{FO})_{start},\ \text{lb/startup} = (F_{FO})_{start}(t_{start})$$

- Working relationships:

  -- For liquid injection incinerators, the following calculations apply for startup fuel consumption:

$$V_i = \frac{Q_{Tmax}}{30,000} = \_\_\_\_\_\_\_\_\_\_ \text{ ft}^3$$

$$D_i = \left(\frac{4V_i}{3\pi}\right)^{1/3} = \_\_\_\_\_\_\_\_\_\_ \text{ ft}$$

$$A_s = 3\pi \; D_i{}^2 = \_\_\_\_\_\_\_\_\_\_ \text{ ft}^2$$

From Figure 13, using the selected t_{start} and T_{I2} values,

$$\left(\frac{Q_{start}}{A_s}\right) = \_\_\_\_\_\_\_\_\_\_ \text{ Btu/ft}^2\text{-hr}$$

$$(F_{FO})_{start} = \frac{\left(\frac{Q_{start}}{A_s}\right) A_s}{19,400} = \_\_\_\_\_\_\_\_ \text{ lb/hr}$$

$$(M_{FO})_{start} = (F_{FO})_{start} \; (t_{start}) = \_\_\_\_\_\_\_\_ \text{ lb/startup}$$

  -- For rotary kiln incinerators and afterburners:

$$V_{i1} = \frac{Q_{Tmax}}{30,000} = \_\_\_\_\_\_\_\_\_\_ \text{ ft}^3$$

$$D_i = \left(\frac{2 \; V_{i1}}{\pi}\right)^{1/3} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ ft}$$

$$A_{s1} = 2\pi \; D_{i1}{}^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ ft}^2$$

$$V_{i2} = 0.0333 \; (q_{TG})_I \left(\frac{T_{I2} + 460}{520}\right) = \_\_\_\_\_\_\_\_ \text{ ft}^3$$

$$D_{i2} = \left(\frac{4 \; V_{i2}}{3\pi}\right)^{1/3} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{ ft}^2$$

$$A_{s2} = 3\pi \; D_{i2}{}^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ ft}^2$$

From Figure 13, using t_{start}, T_{I1}, and T_{I2} values,

$$\left(\frac{Q_{start}}{A_s}\right)_1 = \_\_\_\_\_\_\_\_\_\_\_\_ \text{ Btu/hr-ft}^2$$

$$\left(\frac{Q_{start}}{A_s}\right)_2 = \_\_\_\_\_\_\_\_\_\_\_\_ \text{ Btu/hr-ft}^2$$

$$(F_{FO})_{start} = \frac{\left(\frac{Q_{start}}{A_s}\right)_1 \left(A_{s1}\right) + \left(\frac{Q_{start}}{A_s}\right)_2 \left(A_{s2}\right)}{19{,}400}$$

$= \_\_\_\_\_\_\_\_\_$ lb/hr

$(M_{FO})_{start} = (F_{FO})_{start}\ (t_{start}) = \_\_\_\_\_\_\_\_\_$ lb/startup

-- For hearth incinerators and afterburners:

$V_{i1} = \frac{Q_{Tmax}}{15{,}000} = \_\_\_\_\_\_\_\_\_\_$ ft^3

$W_{i1} = (0.5\ V_{i1})^{1/3} = \_\_\_\_\_\_\_\_\_\_\_$ ft

$A_{s1} = 10\ W_{i1}^2 = \_\_\_\_\_\_\_\_\_\_\_\_$ ft^2

$V_{i2} = 0.0333\ (q_{TG})_I \left(\frac{T_{I2} + 460}{560}\right) = \_\_\_\_\_\_\_\_$ ft^3

$D_{i2} = \left(\frac{4\ V_{i2}}{3\pi}\right)^{1/3} = \_\_\_\_\_\_\_\_\_\_\_\_\_$ ft

$A_{s2} = 3\pi\ D_{i2}^2 = \_\_\_\_\_\_\_\_\_\_\_\_\_$ ft^2

-- From Figure 13, using t_{start}, T_{I1}, and T_{I2} values,

$\left(\frac{Q_{start}}{A_s}\right)_1 = \_\_\_\_\_\_\_\_\_\_\_\_$ Btu/hr-ft^2

$\left(\frac{Q_{start}}{A_s}\right)_2 = \_\_\_\_\_\_\_\_\_\_\_\_$ Btu/hr-ft^2

$$(F_{FO})_{start} = \frac{\left(\frac{Q_{start}}{A_s}\right)_1 \left(A_{s1}\right) + \left(\frac{Q_{start}}{A_s}\right)_2 \left(A_{s2}\right)}{19{,}400}$$

$= \_\_\_\_\_\_\_\_\_$ lb/hr

$(M_{FO})_{start} = (F_{FO})_{start}\ (t_{start}) = \_\_\_\_\_\_\_\_\_\_$ lb/startup

3.4.11 Fuel Oil Feed Pump Capacity

- Purpose and limitations -- The following calculations are designed to estimate capacity requirements for the dual fuel oil feed pumps first addressed in Section 3.3.2.3

- Applicability -- All facilities

- Assumptions:
  - Fuel oil feed pumps are sized to accommodate the larger of two flowrates: (1) the fuel oil feedrate for supplemental heating (F_{FO}) and (2) the fuel oil feedrate for startup [$(F_{FO})_{start}$]
  - Fuel oil density is approximately 7.2 lb/gal
  - The main fuel oil feed circuit is operated at 10:1 recycle to maintain constant nozzle pressure on turndown
- Working relationships:
  - If $F_{FO} > (F_{FO})_{start}$, fuel oil feed pump capacity is given by,

    $(q_{pump})_{FO} = 0.0231\ F_{FO} =$ __________ gpm

    If $F_{FO} < (F_{FO})_{start}$, fuel oil feed pump capacity is given by,

    $(q_{pump})_{FO} = 0.0231\ (F_{FO})_{start} =$ __________ gpm

3.5 WASTE HEAT BOILER OPERATION (OPTIONAL)

This section provides a methodology to estimate potential steam generation and fuel conservation rates from the application of waste heat boilers in hazardous waste incineration facilities. The operations addressed in this section include waste heat boilers themselves, as well as small downstream quenches (plus auxiliaries) needed to reduce boiler exit gas temperatures prior to entering air pollution control devices.

This section and Section 3.6 (Quench Operation) are interchangeable options for cost evaluation because it is not always feasible to apply waste heat boilers for energy recovery. In general, waste heat boiler application is most feasible for category B facilities where the steam generated can be used in the production process(es), thus reducing fuel consumption in the main plant boiler complex. Category A incinerators are usually too small to justify the additional expenditures for heat recovery equipment, and large commercial facilities (category C) frequently do not have a market for the steam produced. The presence of alkali metals or other low-fusion-temperature inorganics in the waste feed also precludes waste heat boiler application, regardless of incinerator capacity, due to excess convective pass fouling problems.

Obviously, other energy recovery methods such as combustion air preheat are viable alternatives to steam generation for many facilities. However, the scope of this study cannot accommodate consideration of every possible energy recovery scheme, so the analysis is limited to steam generation in watertube or firetube boilers.

3.5.1 Steam Generation Rate

- Purpose and limitations -- The following calculations are designed to estimate (1) the recoverable heat in incinerator exit gases and (2) the quantity and quality of steam that may be generated by recovering this heat. The accuracy of these calculations for specific facilities is predicated on the applicability of the assumptions listed below. In general, however, these calculations should be reasonably representative.

- Applicability -- All facilities utilizing waste heat boilers for energy recovery

- Assumptions:

  -- Incineration facilities utilizing waste heat boilers are located close to the plant boiler complex so steam export distances and boiler feedwater pumping distances are relatively short

  -- Steam generated in the waste heat boiler merely reduces the necessary load on the main plant boilers. Feedwater supply and treatment costs are not significantly increased by generating steam in the waste heat boiler rather than generating an equivalent amount of steam in the main boiler facility.

  -- Feedwater is supplied to the waste heat boiler from the boiler plant deaerators via one of the feedwater pumps at 230°F and design waste heat boiler pressure

  -- The waste heat boiler generates saturated steam at 200 psig. Superheaters and economizers are not employed, and the boiler itself is a natural circulation design.

  -- Temperature of the gas leaving the boiler is 550°F

  -- Heat loss from the waste heat boiler is approximately 5 percent of the theoretical recovered heat

  -- Mean heat capacities of combustion gas components over a typical T_{I2} to 550°F temperature range are shown in Table 20

  -- The enthalpy change from feedwater at 230°F to saturated steam at 200 psig is 1,000 Btu/lb

- General relationships:

  -- The general energy balance expression for waste heat boiler operation is:

TABLE 20. MEAN HEAT CAPACITIES OF COMBUSTION GAS COMPONENTS BETWEEN 550° AND 2,000°F

Component[a]	Mean heat capacity ($\overline{C}p$, Btu/lb°F)
CO_2	0.28
H_2O	0.54
O_2	0.25
N_2	0.27

[a] HCl is neglected in this and all subsequent heat balance analyses due to its inherently small concentration (<1 percent) in the gas

(Recovered heat) = (Sensible heat loss of incinerator exit gas) - (Wall heat loss)

-- The steam generation rate is then given by:

$$\text{(Steam generation, lb/hr)} = \frac{\text{(Recovered heat, Btu/hr)}}{\text{(Enthalpy increase of feedwater, Btu/lb)}}$$

- Working relationships:

  -- Based on these general relationships and the preceding assumptions, the working equation for waste heat boiler energy recovery is:

$$Q_{WHB} = 0.95\ [0.28(F_{CO_2})_I + 0.54(F_{H_2O})_I + 0.25\ (F_{O_2})_I + 0.27(F_{N_2})_I]\ (T_{I2} - 550) = \underline{\hspace{3cm}}\ \text{Btu/hr}$$

where $(F_{CO_2})_I$ or $(F_{CO_2})'_I$, etc., values are used as applicable.

  -- The corresponding steam generation rate is:

$$(F_{steam})_{WHB} = \frac{Q_{WHB}}{1,000} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

3.5.2 Fuel Conservation Rate

- Purpose and limitations -- To determine the cost savings associated with waste heat boiler operation, it is necessary to translate the recovered energy into fuel savings for the main plant boiler complex. These fuel savings can be determined rather simply and accurately by the methods presented below, as long as the underlying assumptions are not grossly inapplicable.
- Assumptions:
  - -- No. 2 fuel oil with a higher heating value of 19,400 Btu/lb is burned to generate steam in the main plant boiler complex
  - -- Nominal 80 percent overall fuel-to-steam efficiency is achieved in the main boiler complex during routine operation
  - -- Steam generation in the waste heat boiler does not reduce the main plant boiler load to the point where a significantly lower efficiency than 80 percent is achieved
- General relationship -- The general expression for fuel savings is:

$$(\text{Fuel savings, lb/hr}) =$$

$$\frac{(\text{Waste heat boiler energy recovery, Btu/hr})\begin{pmatrix}\text{Boiler}\\ \text{efficiency}\end{pmatrix}}{(\text{Fuel oil heating value, Btu/lb})}$$

- Working relationship -- Integrating the assumptions listed above into this general expression yields:

$$(F_{FO})_{WHB} = \frac{Q_{WHB}}{24,250} = \underline{\qquad\qquad} \text{ lb/hr}$$

3.5.3 Post-Quench Heat Duty and Water Requirement

- Purpose and limitations -- Although a waste heat boiler considerably reduces the incinerator exit gas temperature (i.e., to 550°F), it is often desirable to include a small quench downstream from the boiler to further reduce gas temperature and saturate the gas with water prior to entering the air pollution control system. This eliminates water evaporation in the scrubbing system and alleviates the potential problems associated with particulate generation in caustic scrubbers. This subsection is designed to estimate the heat duty and water requirements for post-waste heat boiler quenches.

- Applicability -- All facilities employing waste heat boilers
- Assumptions:
  - -- Boiler exit gases are reduced from 550°F to adiabatic saturation temperature in the quench
  - -- Quench pressure is -10 in. W.C., or P_Q = 14.335 psia
  - -- Mean heat capacities of combustion gas components between typical saturation temperatures and 550°F are shown in Table 21
  - -- Quench feedwater is recycled from the quench/scrubber water sump as indicated in Figure 14. Figure 14 shows a generalized system in which a quench, venturi scrubber, and acid gas absorber are all employed, along with a caustic recycle system. As indicated in the following subsections, either the venturi scrubber or acid gas absorber (and caustic addition) may not be needed, depending on the incinerator exit gas composition.
  - -- A high-pressure, spray-type quench is employed with a feedwater requirement two times the requirement for adiabatic saturation. Therefore, the quench water effluent is equal to the saturation feedwater requirement.
- General relationships:
  - -- The quench heat duty is equivalent to the reduction in sensible heat of the combustion gases from 550°F to the adiabatic saturation temperature (T_{sat})

TABLE 21. MEAN HEAT CAPACITIES OF COMBUSTION GAS COMPONENTS BETWEEN 550°F AND SATURATION TEMPERATURE

Gas component	Mean heat capacity, ($\overline{C}p$, Btu/lb°F)
CO_2	0.23
H_2O	0.46
O_2	0.23
N_2	0.25

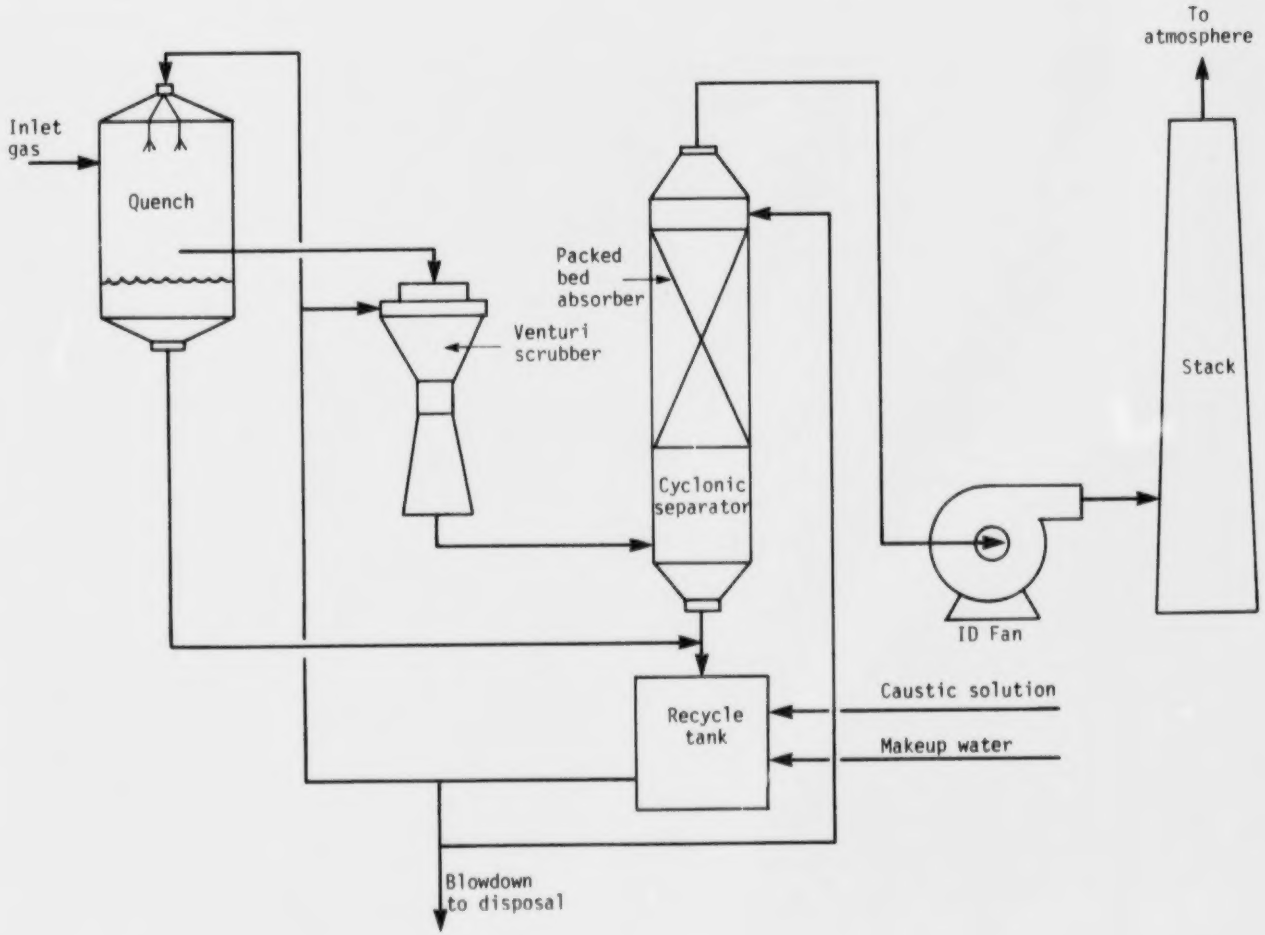

To
atmosphere
Inlet
gas
Quench
Packed
bed
absorber
Venturi
scrubber
Stack
Cyclonic
separator
ID Fan
Caustic solution
Recycle
tank
Makeup water
Blowdown
to disposal

Figure 14. Generalized flow diagram for quench/scrubber system.

3-90

-- The corresponding saturation quench feedwater requirement is given by:

$$(F_{QW})_{sat} = \frac{[\Sigma(F_i)_I\ (\overline{C_p})_i]\ (550-T_{sat})}{\lambda_{sat}} \qquad (4)$$

where λ_{sat} = heat of vaporization of water (Btu/lb) at saturation temperature

-- The adiabatic saturation quench water feedrate is also specified by vapor-liquid equilibrium, as follows:

$$(F_{QW})_{sat} = \frac{(MW)_{H_2O}(\overline{p}_{H_2O})}{(MW)_{DG}\ (P-\overline{p}_{H_2O})}\ (F_{DG}) - (F_{H_2O})_I \qquad (5)$$

where $\overline{p}_{H_2O}$ = vapor pressure of water, psia, at saturation temperature

P = system pressure, psia

-- Combining the heat loss and equilibrium expression yields:

$$\frac{[\Sigma(F_i)_I(\overline{C_p})_i](550-T_{sat})}{\lambda_{sat}} = \frac{(MW)_{H_2O}(\overline{p}_{H_2O})}{(MW)_{DG}\ (P-\overline{p}_{H_2O})}\ (F_{DG}) - (F_{H_2O})_I \qquad (6)$$

-- Equation 6 is solved iteratively because λ_{sat} and $\overline{p}_{H_2O}$ are functions of T_{sat}. The relationship between these variables is presented in Table 22.

-- Because the right side of equation 6 is a strong function of the vapor pressure, $\overline{p}_{H_2O}$, careful interpolation between the values listed in Table 22 is required. Exact agreement between the left and right sides of Equation 6 is not necessary; however, the saturation temperature, T_{sat}, should be determined to the nearest degree.

-- Once T_{sat} is specified, the quench water feed requirement for saturation can be calculated using Equation 4.

-- The actual quench water feedrate is then given by:

$$F_{QW} = 2\ (F_{QW})_{sat}$$

- Working relationships:

-- From expansion and substitution into Equation 6,

TABLE 22. VAPOR PRESSURE AND HEAT OF VAPORIZATION DATA FOR WATER

Saturation temperature, T_{sat}, (°F)	Heat of vaporization, λ_{sat}, (Btu/lb)	Vapor pressure, $\overline{p}_{H_2O}$, (psia)
140	1,014.1	2.8886
145	1,011.2	3.281
150	1,008.2	3.718
155	1,005.2	4.203
160	1,002.3	4.741
165	999.3	5.335
170	996.3	5.992
175	993.3	6.715
180	990.2	7.510
185	987.2	8.383
190	984.1	9.339
195	981.0	10.385
200	977.9	11.526

$$\frac{[0.23(F_{CO_2})_I + 0.46(F_{H_2O})_I + 0.23(F_{O_2})_I + 0.25(F_{N_2})_I]\,(550-T_{sat})}{\lambda_{sat}}$$

$$= \frac{18\ p_{H_2O}}{(MW)_{DG}(14.335 - p_{H_2O})}(F_{DG}) - (F_{H_2O})_I$$

-- Using this expression and Table 22,

T_{sat} = ___________°F

λ_{sat} = ___________Btu/lb

$\overline{p}_{H_2O}$ = ___________psia

-- Applying Equation 4,

$(F_{QW})_{sat}$ =

$$\frac{[0.23(F_{CO_2})_I + 0.46(F_{H_2O})_I + 0.23(F_{O_2})_I + 0.25(F_{N_2})_I]\,(550-T_{sat})}{\lambda_{sat}}$$

= _____________ lb/hr

and,

$F_{QW} = 2\ (F_{QW})_{sat}$ = _____________ lb/hr

-- Finally, the quench water effluent, $(F_{QW})_{eff}$, is equivalent to $(F_{QW})_{sat}$:

$(F_{QW})_{eff} = (F_{QW})_{sat} =$ ____________ lb/hr

-- For use in subsequent subsections, it is convenient to convert these flowrates from lb/hr to gpm as follows:

$q_{QW} = 0.002\ F_{QW} =$ ______________ gpm

$(q_{QW})_{eff} = 0.002\ (F_{QW})_{eff} =$ ________________ gpm

3.5.4 Quench Feed Pump Power Requirement

- Purpose and limitations -- The following calculations are intended to estimate quench feedwater pump power requirements based on the feedwater rates calculated in the preceding section
- Applicability -- All facilities employing waste heat boilers
- Assumptions:

  -- Pump discharge pressure is 100 psig (a high-pressure spray-type quench system is assumed in Section 3.5.3)

  -- Overall pump/motor efficiency is 50 percent
- General relationship -- See previous sections addressing pump power requirements
- Working relationship:

$(P_{pump})_{QW} = 2.33 \times 10^{-4}\ F_{QW} =$ ___________ hp

3.5.5 Saturated Gas Flow and Composition

- Purpose and limitations -- This section is designed to estimate the flowrate and composition of saturated gas leaving the quench. These quantities must be known for downstream, scrubbing system evaluation.
- Applicability -- All facilities utilizing waste heat boilers.
- Assumptions:

  -- Absorption of CO_2, N_2, and O_2 in the quench water effluent is negligible

  -- For other assumptions, see Section 3.5.3

- Working relationships:

  -- Component mass flowrates in the saturated gas leaving the quench are:

  $(F_{CO_2})_{sat} = (F_{CO_2})_I =$ __________ lb/hr

  $(F_{O_2})_{sat} = (F_{O_2})_I =$ __________ lb/hr

  $(F_{N_2})_{sat} = (F_{N_2})_I =$ __________ lb/hr

  $(F_{H_2O})_{sat} = (F_{H_2O})_I + (F_{QW})_{sat} =$ __________ lb/hr

  -- Total gas flowrates are given by:

  $(F_{TG})_{sat} = (F_{DG})_I + (F_{H_2O})_{sat} =$ __________ lb/hr

  $(q_{TG})_{sat} = (q_{DG})_I + 0.352\ (F_{H_2O})_{sat} =$ __________ scfm

  -- Finally, saturated gas pressure leaving the quench is:

  $P_Q = 14.335$ psia

3.6 QUENCH OPERATION (Optional)

This section addresses water and power requirements for full-scale quench systems installed in hazardous waste incineration facilities which do not employ waste heat boilers.

3.6.1 Heat Duty and Water Requirement

- Purpose and limitations -- The calculations presented in this subsection are virtually identical to those outlined in Section 3.5.3 for post-waste heat boiler quenches. However, as discussed below, some of the underlying assumptions and physical constants are different because full-scale quenches reduce gas temperatures across a much larger temperature range than post-WHB quenches.

- Applicability -- All facilities which do not employ waste heat boilers

- Assumptions:

  -- Quench pressure is -6 in. W.C., $P_Q = 14.48$ psia

  -- Mean heat capacities of combustion gas components between saturation temperatures and normal T_{I2}'s are shown in Table 23

TABLE 23. MEAN HEAT CAPACITIES OF COMBUSTION GAS COMPONENTS BETWEEN 2,000°F AND SATURATION TEMPERATURE

Gas component	Mean heat capacity ($\overline{C_p}$, Btu/lb-°F)
CO_2	0.26
H_2O	0.53
O_2	0.24
N_2	0.27

-- All other assumptions are the same as those listed in Section 3.5.3

- Working relationships:

-- Substituting appropriately into Equation 6 yields the relationship:

$$\frac{[0.26(F_{CO_2})_I + 0.53(F_{H_2O})_I + 0.24\ (F_{O_2})_I + 0.27(F_{N_2})_I]\ [T_{I2} - T_{sat}]}{\lambda_{sat}}$$

$$= \frac{18\ \overline{p}_{H_2O}}{(MW)_{DG}\ (14.48 - \overline{p}_{H_2O})}\ (F_{DG}) - (F_{H_2O})_I$$

-- Using this expression and Table 22,

T_{sat} = ______________ °F

λ_{sat} = ______________ Btu/lb

$\overline{p}_{H_2O}$ = ______________ psia

-- The water requirement for saturation is then given by:

$$(F_{QW})_{sat} = \frac{[0.26(F_{CO_2})_I + 0.53(F_{H_2O})_I + 0.24\ (F_{O_2})_I + 0.27(F_{N_2})_I]\ [T_{I2} - T_{sat}]}{\lambda_{sat}}$$

= ______________ lb/hr

therefore,

$F_{QW} = 2(F_{QW})_{sat} =$ ____________ lb/hr

$q_{QW} = 0.002\ F_{QW} =$ ____________ gpm

$(F_{QW})_{eff} = (F_{QW})_{sat} =$ ____________ lb/hr

$(q_{QW})_{eff} = 0.002\ (F_{QW})_{eff} =$ ____________ gpm

3.6.2 Quench Feed Pump Power Requirement

- Purpose, limitations, and applicability -- This section is a corollary to Section 3.5.4 for post-waste heat boiler quenches
- Assumptions:

  -- Overall pump/motor efficiency is 60 percent

  -- See Section 3.5.4 for additional assumptions
- Working relationship -- The modified expression for pump power requirement is:

$(P_{pump})_{QW} = 1.94 \times 10^{-4}\ F_{QW}$

$=$ ____________ hp

3.6.3 Saturated Gas Flow and Composition

- Purpose, limitations, applicability, and assumptions:

  This section is corollary to Section 3.5.5 for post-waste heat boiler quenches.
- Working relationships:

$(F_{CO_2})_{sat} = (F_{CO_2})_I =$ ____________ lb/hr

$(F_{O_2})_{sat} = (F_{O_2})_I =$ ____________ lb/hr

$(F_{N_2})_{sat} = (F_{N_2})_I =$ ____________ lb/hr

$(F_{H_2O})_{sat} = (F_{H_2O})_I + (F_{QW})_{sat} =$ ____________ lb/hr

$(F_{TG})_{sat} = (F_{DG})_I + (F_{H_2O})_{sat} =$ ____________ lb/hr

$(q_{TG})_{sat} = (q_{DG})_I + 0.352\ (F_{H_2O})_{sat} =$ ____________ scfm

$P_Q = 14.48$ psia

3.7 SCRUBBER SYSTEM OPERATION

The objectives of this section are to determine (1) generic scrubber system requirements based on the desired particulate and HCl removal efficiencies, (2) pressure drops across the scrubbing system, (3) makeup water requirements, (4) caustic soda requirements for HCl neutralization, and (5) scrubber blowdown rates. These quantities must be calculated to determine capital requirements and overall facility consumption of water and chemicals, waste disposal costs, and ID fan power requirements.

3.7.1 Venturi Scrubber Applicability

- Purpose and limitations -- Guidelines are presented below to determine whether or not particulate scrubbing needs to be considered for the facility under evaluation. These guidelines are conservative, which is consistent with the philosophy of this study.
- Applicability -- All facilities
- Assumptions and general guidelines:
  - -- While numerous generic control devices are available for particulate removal, only venturi scrubbers are considered in this study. This is justified by the fact that venturi scrubbers are by far the predominant particulate control device used in hazardous waste incineration facilities.
  - -- The required particulate removal efficiency (η_{part}) is determined by:

$$\eta_{part}, \text{ percent} = 100 \left[1 - \frac{(C_{part})_{VS}}{(C_{part})_I} \right]$$

    where $(C_{part})_{VS}$ is the particulate loading in the exit gas, gr/dscf, specified in Section 2, and $(C_{part})_I$ is the estimated loading in the combustion gas, gr/dscf
  - -- A variable fraction of larger particulate matter is removed from the gas in the quench, as fallout to waste heat boiler dust hoppers, and in the acid gas absorber (if utilized). However, smaller particles, particularly submicron particles, are not typically removed by these mechanisms.
  - -- Particulate emissions from hazardous waste incinerators are usually composed of extremely fine particles; in some cases mass mean diameters are <1 μm
  - -- Therefore, it is conservatively assumed that a venturi scrubber is needed if $(C_{part})_I > (C_{part})_{VS}$, or correspondingly if $\eta_{part} > 0$

- Although this may be a conservative assumption in borderline cases, it will not overstate the capital or O&M costs to a substantial degree. Capital costs for venturi scrubbers, while not insignificant, are not nearly as substantial as the costs for other facility components. In terms of O&M cost, the major impact of venturi scrubber operation is on the ID fan power requirement, which is largely a function of venturi pressure drop for a given gas flowrate. Venturi pressure drop is estimated in Section 3.7.4 as a function of the required removal efficiency (η_{part}) so system pressure drop is not arbitrarily increased by venturi scrubber inclusion.

- Decision criteria:

  - Calculate the required particulate removal efficiency, (η_{part}):

$$\eta_{part} = 100 \left[1 - \frac{(C_{part})_{VS}}{(C_{part})_{I}} \right] = \_\_\_\_\_\_\_\_\_\_ \text{ percent}$$

  - If $\eta_{part} \leq 0$, proceed to Section 3.7.5. No venturi scrubber is required.

  - If $\eta_{part} > 0$, a venturi scrubber is required. Proceed to the following subsection.

3.7.2 Venturi Scrubber Feedrate Requirement and Effluent Flow

- Purpose and limitations -- This section presents general guidelines to estimate venturi scrubber feedrate requirements and effluent flowrates. These guidelines should be representative of typical facilities, although they may not correlate well for specific design cases.

- Applicability -- All facilities employing venturi scrubbers

- Assumptions:

  - The venturi scrubber liquid-to-gas ratio is 10 gal/1,000 acf of gas at the inlet

  - Gas enters the venturi scrubber from the quench at saturation temperature (T_{sat})

- General relationships:

  - The volumetric gas flowrate to the venturi at standard conditions is equivalent to $(q_{TG})_{sat}$, scfm

-- The actual gas flowrate is given by:

$$(q_{TG})_{sat} \left(\frac{T_{sat} + 460}{520}\right) \left(\frac{14.696}{P_Q}\right),$$

where P_Q is the absolute pressure at the quench exit, psia.

-- Liquid feed to the venturi is then estimated by multiplying this gas flowrate by the liquid-to-gas ratio estimate given above

- Working relationships:

-- Based on these considerations, the venturi scrubbant feedrate, q_{VSW}, is given by:

$$q_{VSW} = 0.01\ (q_{TG})_{sat} \left(\frac{T_{sat} + 460}{520}\right) \left(\frac{14.696}{P_Q}\right) = \_\_\_\_\_\_ \text{gpm}$$

$$F_{VSW} = 500\ q_{VSW} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{lb/hr}$$

-- Because the inlet gas is already saturated, the liquid effluent is given by:

$$(q_{VSW})_{eff} = q_{VSW} = \_\_\_\_\_\_\_\_ \text{gpm}$$

$$(F_{VSW})_{eff} = F_{VSW} = \_\_\_\_\_\_\_\_ \text{lb/hr}$$

3.7.3 Venturi Scrubber Recycle Pump Power Requirement

- Purpose and limitations:

-- The following calculations are designed to estimate pumping power requirements for the venturi scrubber feed solution. Any limitations in the accuracy of these calculations are due primarily to the assumptions used to determine q_{VSW}.

- Applicability -- All facilities employing venturi scrubbers

- Assumptions:

-- The venturi scrubbing solution is pumped from a recycle tank which receives the quench effluent, venturi scrubber effluent, and acid gas absorber effluent, if an absorber is used

-- This recycle tank also serves as the point for fresh makeup water addition

-- Venturi recycle pump discharge pressure is nominally 30 psig

-- Overall pump/motor efficiency is 60 percent

- Working relationships -- Based on these assumptions and the general power expression presented in several preceding subsections, the working equation for venturi scrubbant feed pump power is:

  $$(P_{pump})_{VSW} = 0.0292\ q_{VSW} = \underline{\hspace{6em}}\ hp$$

3.7.4 Venturi Scrubber Pressure Drop Requirement

- Purpose and limitations -- This section is designed to estimate venturi scrubber pressure drop requirement as a function of (1) the required particulate removal efficiency, and (2) approximate particle size distribution data supplied by the user. A number of assumptions and emperical relationships are involved in the calculation procedure, so the results will only be approximate. Actual pressure drop requirements will depend on scrubber geometry, method of liquid introduction, and particle wetability, among other factors, which cannot be precisely addressed within the scope of this study.

- Applicability -- All facilities utilizing venturi scrubbers

- Assumptions and general relationships:

  -- Overall particulate collection efficiency for a given venturi pressure drop is dependent on two major factors:

  1. Particle size distribution in the inlet gas. This refers to the mass fraction of total particulate, X_{part}, contained within each incremental range of aerodynamic particle diameters, $D_{pi} \rightarrow D_{p(i+1)}$. The distribution of particulate mass may be expressed by

     $$(X_{part})_{i,\ i+1} = \delta\ (D_p)_{i,\ i+1}$$

     where δ denotes a functional relationship between the mass fraction of particulate $(X_{part})_{i,\ i+1}$, contained within the range of particle diameters, $(D_p)_i \rightarrow (D_p)_{i+1}$. The symbol $(D_p)_{i,\ i+1}$ represents the arithmetic mean of $(D_p)_i$ and $(D_p)_{i+1}$.

     Therefore, the total particulate mass is:

     $$\sum_{(D_p)_i = (D_p)_{min}}^{(D_p)_i = (D_p)_{max}} (X_{part})_{i,\ i+1}$$

where $(D_p)_{min}$ and $(D_p)_{max}$ are the minimum and maximum particle diameters, respectively.

2. The second major factor affecting overall collection efficiency is the fractional penetration for each range of particle diameters $(P_t)_{i,\ i+1} = \delta\ (D_p)_{i,\ i+1}$ where δ denotes a relationship between fractional penetration, $(P_t)_{i,\ i+1}$ in the $(D_p)_i \rightarrow (D_p)_{i+1}$ particle diameter range, and $(D_p)_{i,\ i+1}$.

-- Integrating the expressions for $(X_{part})_{i,\ i+1}$ and $(P_t)_{i,\ i+1}$, yields the following general equation for overall penetration, $\overline{P_t}$:

$$\overline{P_t} = \sum_{(D_p)_{min}}^{(D_p)_{max}} (X_{part})_{i,\ i+1}\ (P_t)_{i,\ i+1}$$

This overall penetration is related to overall collection efficiency by:

η_{part}, percent = $100\ (1 - \overline{P_t})$

-- An iterative procedure is required to solve these general equations and find the pressure drop which yields the desired overall collection efficiency (η_{part}). The steps of this procedure are as follows:

- Estimate the particle size distribution so that $(D_p)_i \rightarrow (D_p)_{i+1}$ ranges are specified, and an $(X_{part})_{i,\ i+1}$ value is determined for each $(D_p)_{i,\ i+1}$ value
- Select a reasonable ΔP value for the particle size distribution in question
- Use this ΔP value along with empirical relationships to estimate the venturi throat velocity (v_t)
- Use this venturi throat velocity, along with other system parameters, to empirically estimate the mean water droplet size ($\overline{D_d}$)
- Using the estimated v_t and $\overline{D_d}$ values, along with other system parameters, estimate fractional penetration, $(P_t)_{i,\ i+1}$, for each $(D_p)_{i,\ i+1}$ value

- Compare this calculated collection efficiency with the desired efficiency (η_{part})

- Select a new ΔP value and repeat the calculations until the predicted efficiency is equivalent to η_{part}. New ΔP values should be selected on the basis that higher pressure drops yield better collection efficiencies for the same particle size distribution.

-- Details of each step in this iterative procedure are presented below. The calculations themselves are relatively complex and repetitive, so computer assistance is highly recommended.

- Estimation of particle size distribution:

  -- In the unlikely event that measured particle size data are available (impactor data, for example), the $(X_{part})_{i,\ i+1}$ versus $(D_p)_{i,\ i+1}$ relationship can be constructed directly in tabular form as shown by example format in Table 24.

  If available, these data should be entered in Section 2.

  -- More likely, however, the size distribution will not be known apriori. In this case, a log normal size distribution can be assumed, and $(X_{part})_{i,\ i+1}$ versus $(D_p)_{i,\ i+1}$ data sets can be theoretically estimated by specifying the geometric mean particle diameter (D_{pg}) and the geometric standard deviation (σ_{pg}).

  -- Limited data from one scrubber manufacturer show that:

TABLE 24. FORMAT FOR PRESENTATION OF PARTICLE SIZE DISTRIBUTION DATA

$(D_p)_i - (D_p)_{i+1}$, μm	$(D_p)_{i,\ i+1} = \frac{(D_p)_i + (D_p)_{i+1}}{2}$, μm	$(X_{part})_{i,\ i+1}$
$D_{p1} - D_{p2}$	$(D_p)_{1,2}$	$(X_{part})_{1,2}$
$D_{p2} - D_{p3}$	$(D_p)_{2,3}$	$(X_{part})_{2,3}$
	--------------------etcetera--------------------	

For hospital wastes, $D_{pg} = 2.75\ \mu m$ and $\sigma_{pg} \approx 2.0$
For pharmaceutical wastes, $D_{pg} = 2.0\ \mu m$ and $\sigma_{pg} \approx 2.5$
For phosphrous containing pesticides, $D_{pg} = 0.7\ \mu m$ and $\sigma_{pg} \approx 1.5$

The latter is considered virtually a worst case in terms of fine particle collection for hazardous waste incinerator applications.

-- These values are intended for user guidance only; other D_{pg} and σ_{pg} data can be utilized. Regardless of which values are used, however, they should be specified in Section 2.

-- Once D_{pg} and σ_{pg} are specified, the particle diameter cuts, $(D_p)_i \rightarrow (D_p)_{i+1}$, can be selected. Recommended minimum and maximum values are $(D_p)_{min} = 0.1\ D_{pg}$ and $(D_p)_{max} = 10\ D_{pg}$. Intermediate cut diameters should be spaced in geometric intervals with approximately 10 such intervals below D_{pg} and 10 intervals above D_{pg}. For example, if $D_{pg} = 1.0\ \mu m$, the recommended intervals would be 0.1 to 0.2 µm, 0.2 to 0.3 µm, etc. up to 9.0 to 10.0 µm.

-- The log-normal curve is then constructed as a function of $(D_p)_i$:

$$\delta\,(D_p)_i = \frac{1}{\sqrt{2\pi}\ \ell n\ \sigma_{pg}} \exp \left\{ -0.5 \left[\frac{\ell n[(D_p)_i/D_{pg}]}{\ell n\ \sigma_{pg}} \right]^2 \right\}$$

-- The mass fraction of particulate in the $(D_p)_i \rightarrow (D_p)_{i+1}$ particle diameter range, $(X_{part})_{i,\ i+1}$ is then given by the area under the log normal curve between $(D_p)_i$ and $(D_p)_{i+1}$, divided by the total area under the curve between $(D_p)_{min}$ and $(D_p)_{max}$:

$$(X_{part})_{i,\ i+1} = \frac{\displaystyle\int_{(D_p)_i}^{(D_p)_{i+1}} \delta(D_p)_i\ d(D_p)_i}{\displaystyle\int_{(D_p)_{min}}^{(D_p)_{max}} \delta(D_p)_i\ d(D_p)_i}$$

where, again, $\delta(D_p)_i$ signifies the log normal relationship in this context, and $d(D_p)_i$ signifies an infinitesimally small particle diameter interval.

  - This general relationship can be used to generate $(X_{part})_{i,\ i+1}$ versus $(D_p)_{i,\ i+1}$ data sets. Standardized computer subroutines are available to perform these calculations, so the mechanics are not addressed in this report.

- Selection of an initial ΔP value:

  - Selection of the initial ΔP (in. W.C.) is not a critical concern because the calculation procedure is iterative anyway. However, the number of iterations can be reduced by judicious selection of ΔP.

  - For cases where D_{pg} = 2 to 3 µm, an initial input of ΔP = 30- to 40-in. W.C. is reasonable

  - For larger mean particle sizes, ΔP = 10- to 20-in. W.C. is a realistic first estimate, and for mean particle sizes down to or slightly below 1.0 µm, ΔP = 60- to 100-in. W.C. is a reasonable input.

  - Because the desired collection efficiency (η_{part}) also plays a major role in determining the required ΔP, the initial pressure drop estimate may not follow the previously mentioned guidelines. However, an initial ΔP estimate should be provided in Section 2.

- Estimation of venturi throat velocity

  - Venturi pressure drop and throat velocity are approximately related by the Calvert equation,

$$\Delta P = 5 \times 10^{-5}\ v_t^2\ (q_L/q_G)$$

where ΔP = pressure drop. in. W.C.
v_t = throat velocity, ft/sec
q_L/q_G = liquid:gas ratio, gal/1,000 ft^3

  - Therefore, the throat velocity (v_t) is given by:

$$v_t = \sqrt{\frac{20{,}000\ \Delta P}{(q_L/q_G)}}$$

- Estimation of mean water droplet size

  - Based on empirical data (Reference 4), the Sauter mean droplet size from liquid atomization in the venturi throat is given by:

$$\overline{D_d} = \frac{283{,}000 + 793\,(q_L/q_G)^{1.922}}{(0.72667\ v_t)^{1.602}}$$

where $\overline{D_d}$ = Sauter mean droplet size, μm

-- This empirical relationship was developed using a non-wetted, fixed-throat venturi scrubber with water injected at a point where the gas velocity was 72 to 73 percent of the throat velocity. Thus, the predicted $\overline{D_d}$ value may not be highly accurate for other scrubber geometries.

- Estimation of fractional penetration

-- Based on modification of the equations presented in Reference 5, fractional penetration is related to aerodynamic particle diameter by the following relationships:

$$P_t = \exp\left[\frac{2.3732 \times 10^{-10}\,(q_L/q_G)\ v_t\ \rho_L\ \overline{D_d}}{\mu_G}\ \delta(K_{pt},f)\right]$$

where (q_L/q_G) = liquid-to-gas ratio, gal/1,000 acf
v_t = throat velocity, ft/sec
ρ_L = liquid density, lb/ft^3
$\overline{D_d}$ = mean droplet diameter, μm
μ_G = gas viscosity, poise
δ = a functional relationship
K_{pt} = inertial impaction parameter
f = "unknown factor"

-- The inertial impaction parameter (K_{pt}) is given by:

$$K_{pt} = \frac{1.6933 \times 10^{-4}\ (D_p)^2\ v_t}{\mu_G\ \overline{D_d}}$$

where D_p = aerodynamic particle diameter, μm

-- The "unknown factor" (f) is an empirical constant which absorbs the influence of parameters not explicitly addressed in the preceding equations, such as liquid maldistribution, particle growth, condensation, and collection by means other than impaction. Calvert (Reference 6) suggests a value of f = 0.5 for large scrubbers.

-- The quantity $\delta(K_{pt}, f)$ is given by:

$$\delta(K_{pt}, f) = \frac{1}{K_{pt}} \left[-0.7 - K_{pt}f + 1.4 \ln \left(\frac{K_{pt}f + 0.7}{0.7} \right) + \frac{0.49}{0.7 + K_{pt}f} \right]$$

-- Density of water (ρ_L) is relatively independent of temperature over the range of saturation temperatures encountered at the venturi inlet. Assuming a mid-range saturation temperature of 175°F, $\rho_L = 60.7\ \mathrm{lb/ft^3}$.

-- Viscosities of saturated gas components can also be approximated with little error by assuming a saturation temperature of 175°F. These viscosities are shown below.

$\mu_{CO_2} = 1.73 \times 10^{-4}$ poise

$\mu_{O_2} = 2.34 \times 10^{-4}$ poise

$\mu_{N_2} = 2.02 \times 10^{-4}$ poise

$\mu_{H_2O} = 1.15 \times 10^{-4}$ poise

-- Viscosity of the gas mixture (μ_G) is approximated by (Reference 1):

$$\mu_G,\ \text{poise} = \frac{\Sigma\, y_i\ \mu_i\ (MW)_i^{0.5}}{\Sigma\, y_i\ (MW)_i^{0.5}}$$

where y = mole fraction of component i. And because $y_i \propto q_i$, the volumetric flowrate of gas component i,

$$\mu_G,\ \text{poise} = \frac{\Sigma\, q_i\ \mu_i\ (MW)_i^{0.5}}{\Sigma\, q_i\ (MW)_i^{0.5}}$$

-- By combining the preceding relationships, $(P_t)_{i,\ i+1}$ versus $(D_p)_{i,\ i+1}$ values can be estimated for each particle size interval

- Estimation of overall penetration and collection efficiency

-- As previously indicated, overall penetration is given by:

$$\overline{P_t} = \sum_{(D_p)_{min}}^{(D_p)_{max}} (X_{part})_{i,\ i+1} (P_t)_{i,\ i+1}$$

-- Predicted collection efficiency is then given by:

$$\eta_{part},\ \text{percent} = 100\ (1 - \overline{P_t})$$

- Comparison of calculated and desired collection efficiencies

  -- Comparison of calculated and desired collection efficiencies indicates (1) whether or not the assumed pressure drop was reasonably accurate, (2) whether a lower or higher pressure drop should be assumed for the next iteration (if the calculated and desired collection efficiencies do not agree), and (3) whether or not a "default" pressure drop should be assumed.

  -- If the calculated and desired collection efficiencies agree within approximately 0.5 percent overall (e.g., 96.0 percent versus 96.5 percent), the pressure drop assumed for $\overline{P_t}$ calculation can be taken as the required pressure drop for the venturi, ΔP_{VS}. The error involved in the $\overline{P_t}$ calculation procedure is usually greater than a 0.5 percent difference in calculated versus desired collection efficiency.

  -- If the calculated collection efficiency is less than the desired collection efficiency (η_{part}) by more than 0.5 percent overall, then a higher ΔP value should be selected and the preceding steps should be repeated. Conversely, if the calculated collection efficiency is greater than the desired collection efficiency, then a lower ΔP value should be selected and the preceding steps should be repeated.

  -- Finally, it is advisable to set minimum and maximum "default" pressure drops for practical purposes. The recommended minimum default value is $(\Delta P_{VS})_{min}$ = 10-in. W.C. The recommended maximum default value is $(\Delta P_{VS})_{max}$ = 100-in. W.C. The reasons for establishing these default values are two-fold:

  1. The equations presented earlier in this section tend to overestimate collection of particles larger than 1 μm, and to underestimate collection of particles smaller than 1 μm. This conclusion

is based on vendor-supplied collection efficiency data.

2. The particle size distribution is specified by the user, and may be hypothetical in many cases. Thus, the default pressure drop specifications prevent unrealistic particle size distribution inputs from unduly influencing the overall O&M cost estimate.

- Working relationships:

  -- Based on the assumptions and empirical relationships presented above, the following procedures are recommended to estimate the required pressure drop (ΔP_{VS}) for venturi scrubber operation.

  1. Estimate the particle size distribution

     -- If particle size data are available, then specify the aerodynamic size distribution in tabular form as previously indicated in Table 24. These data should be input in Section 2.

     -- If particle size distribution data are not available, then the log-normal size distribution can be assumed and the mass median particle diameter (D_{pg}) and the geometric standard deviation of particle diameters (σ_{pg}) should be specified here and in Section 2.

     D_{pg} = ____________ μm

     σ_{pg} = ____________ μm

     -- Standard computer subroutines for the log-normal distribution can then be used to construct the $(X_{part})_{i,\ i+1}$ versus $(D_p)_{i,\ i+1}$ relationship

  2. Specify the initial pressure drop estimate and default pressure drop values in Section 2

     $(\Delta P_{VS})_{initial}$ = _______________ in. W.C.

     $(\Delta P_{VS})_{min}$ = 10-in. W.C.

     $(\Delta P_{VS})_{max}$ = 100-in. W.C.

3. Estimate the venturi throat velocity

-- Assuming (q_L/q_G) = 10 gal/1,000 acf, venturi throat velocity is given by,

$$v_t = 2{,}000\ \Delta P = \_\_\_\_\_\_\_\_\_\_\ \text{ft/sec}$$

4. Estimate the mean water droplet size

-- Again, assuming (q_L/q_G) = 10 gal/1,000 acf, the Sauter mean droplet size is given by,

$$\overline{D_d} = \frac{582{,}497}{{v_t}^{1.602}} = \_\_\_\_\_\_\_\_\_\_\ \mu m$$

5. Calculate the viscosity of the saturated inlet gas:

$$(\mu_{TG})_{sat} = \frac{1.65(F_{CO_2})_{sat} + 2.62(F_{O_2})_{sat} + 2.42(F_{N_2})_{sat} + 1.72(F_{H_2O})_{sat}}{10{,}000\left[0.955(F_{CO_2})_{sat} + 1.12(F_{O_2})_{sat} + 1.2(F_{N_2})_{sat} + 1.49(F_{H_2O})_{sat}\right]}$$

$$= \_\_\_\_\_\_\_\_\_\_\ \text{poise}$$

6. Calculate the inertial impaction parameter for each $(D_p)_{i,\ i+1}$ value:

$$(K_{pt})_{i,\ i+1} = \frac{1.6933 \times 10^{-4}(D_p)^2_{i,\ i+1}\, v_t}{(\mu_{TG})_{sat}\, \overline{D}_d}$$

$$= \_\_\_\_\_\_\_\_\_\_$$

7. Calculate the corresponding $\delta(K_{pt},f)_{i,\ i+1}$ values:

$$\delta(K_{pt},f)_{i,\ i+1} = \frac{1}{(K_{pt})_{i,\ i+1}}\left[-0.7 - 0.5(K_{pt})_{i,\ i+1} + 1.4\ln\left(\frac{0.7 + 0.5(K_{pt})_{i,\ i+1}}{0.7}\right) + \frac{0.49}{0.7 + 0.5(K_{pt})_{i,\ i+1}}\right] = \_\_\_\_\_\_\_\_\_\_$$

8. Calculate the fractional penetration for each $(D_p)_{i,\ i+1}$ value:

$$(P_t)_{i,\ i+1} = \exp\left[\frac{1.44 \times 10^{-7} v_t \overline{D_d}}{(\mu_{TG})_{sat}} \delta(K_{pt}, f)_{i,\ i+1}\right]$$

= ____________

9. Calculate the overall penetration:

$$\overline{P_t} = \sum_{(D_p)_{min}}^{(D_p)_{max}} (X_{part})_{i,\ i+1} (P_t)_{i,\ i+1}$$

= ____________

10. Determine the calculated collection efficiency for $(\Delta P_{VS})_{initial}$:

$(\eta_{part})_{calc} = 100(1 - \overline{P_t})$ = ____________%

11. Compare $(\eta_{part})_{calc}$ to the desired collection efficiency, (η_{part}). If

$|\eta_{part} - (\eta_{part})_{calc}| \leq 0.5\%$, set

$\Delta P_{VS} = (\Delta P_{VS})_{initial}$ = ____________ in. W.C.

If $|\eta_{part} - (\eta_{part})_{calc}| > 0.5\%$, return to step (2) and select a new $(\Delta P_{VS})_{initial}$ value.

If the iteration proceeds to the point where $(\Delta P_{VS})_{initial} < (\Delta P_{VS})_{min}$, then set

$\Delta P_{VS} = (\Delta P_{VS})_{min}$ = ____________ in. W.C.

Correspondingly, if the iteration proceeds to the point where $(\Delta P_{VS})_{initial} > (\Delta P_{VS})_{max}$, then set

$\Delta P_{VS} = (\Delta P_{VS})_{max}$ = ____________ in. W.C.

3.7.5 HCl Absorber Application and Caustic Feedrate Requirement

- Purpose and limitations -- This section presents guidelines to determine (1) whether or not an absorption column should be considered for HCl removal and (2) the caustic addition rate needed for HCl neutralization if an absorber is required. These guidelines are quite general for the purposes of this study because a wide range of possible waste chlorine contents must be addressed.

- Applicability -- All facilities burning chlorinated wastes

- Assumptions and guidelines:

  -- For the purposes of this study, it is recommended that absorber addition and operation be considered if the waste(s) contains more than 0.5 percent organic chlorine.

  -- Incidental removal of HCl is achieved in quench systems and wet scrubbers designed for particulate removal, but $\geq$90 percent HCl control usually requires the addition of an absorption column. Current regulations specify $\geq$99 percent HCl removal.

  -- Packed-bed absorbers are used for HCl removal, which is typical of current industry practice.

  -- A caustic, recycle scrubbing system is used whereby the absorber effluent flows to a recycle tank at its base. This recycle tank also receives the quench and venturi scrubber effluents.

  -- Caustic solution is added to the line leading from the recycle tanks to the venturi scrubber/absorber recycle pumps. Thus, for material balance purposes, it can be assumed that the caustic solution is added to the recycle tank.

  -- Either caustic soda or lime can be used for HCl neutralization; however, 50 percent caustic soda solution is assumed for the purposes of this study

  -- HCl neutralization proceeds by the reaction:

  $$HCl + NaOH = NaCl + H_2O$$

  therefore, the theoretical NaOH requirement is 1.1 lb NaOH/lb HCl in the gas, or 2.2 lb of 50 percent caustic soda solution per lb of HCl

  -- The desired pH of the recycle solution is 7.0, so the theoretical caustic soda requirement and the actual feedrate are equivalent

- Working relationship -- Based on these assumptions, the feedrate of caustic soda solution is given by:

$$F_{CSS} = 2.2\ (F_{HCl})_I = \underline{\hspace{6cm}}\ \text{lb/hr}$$

3.7.6 Caustic Solution Feed Pump Capacity and Power Requirement

- Purpose and limitations -- The following calculations are designed to estimate pump capacity and power requirements to transfer the 50 percent caustic soda solution from onsite storage to the scrubbing system recycle loop
- Applicability -- All facilities employing caustic scrubbing for HCl removal
- Assumptions:
  - -- Pump discharge pressure is 30 psig
  - -- Density of 50 percent caustic soda solution is 84.8 lb/ft^3 (1.36 specific gravity)
  - -- Overall pump/motor efficiency is 40 percent
- Working relationships:
  - -- Based on these assumptions, the expression relating required horsepower and caustic solution feedrate is:

$$(P_{pump})_{CSS} = 6.43 \times 10^{-5} F_{CSS} = \underline{\hspace{3cm}} \text{hp}$$

  - -- Pump capacity is given by:

$$(q_{pump})_{CSS} = 0.0015 F_{CSS} = \underline{\hspace{3cm}} \text{gpm}$$

3.7.7 Absorber Solution Feedrate Requirement and Effluent Flow

- Purpose and limitations -- This section presents general guidelines to estimate the recycle flowrate of scrubbing solution to the top of the absorption column. These guidelines should be representative for typical facilities, although they may not correlate well for specific design cases.
- Applicability -- All facilities employing HCl absorbers
- Assumptions:
  - -- The absorption column liquid-to-gas ratio is 12 gal/1,000 acf of gas at inlet conditions
  - -- Inlet gas temperature and composition is the same as that at the quench exit, although the absolute pressure will be less than quench pressure if a venturi scrubber is employed

- Working relationships:

  -- Based on these assumptions, the absorber feed requirement is given by:

$$q_{AbW} = 0.012(q_{TG})_{sat}\left(\frac{T_{sat} + 460}{520}\right)\left(\frac{14.696}{P_Q - \Delta P_{VS}/27.72}\right)$$

$$= \_\_\_\_\_\_\_\_\_\_ \text{ gpm}$$

  -- In terms of mass flow:

$$F_{AbW} = 500\ q_{AbW} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{lb/hr}$$

  -- Because the inlet gas is already saturated with water, water feedrate and discharge from the absorber are equivalent. Thus,

$$(q_{AbW})_{eff} = q_{AbW} = \_\_\_\_\_\_\_\_\_\_ \text{ gpm}$$

$$(F_{AbW})_{eff} = F_{AbW} = \_\_\_\_\_\_\_\_\_\_ \text{ lb/hr}$$

3.7.8 Absorber Solution Recycle Pump Power Requirement

- Purpose and limitations -- The following calculations are designed to estimate pumping power requirements for the absorber feed solution. Any limitations in the accuracy of these calculations are due primarily to the assumptions used to determine q_{AbW}.
- Applicability -- All facilities employing HCl absorbers
- Assumptions:

  -- The absorber feed solution is pumped from a recycle tank which receives the quench, venturi scrubber, and absorber effluents

  -- Absorber recycle pump discharge pressure is nominally 30 psig

  -- Overall pump/motor efficiency is 60 percent

- Working relationship:

  -- Based on these assumptions, the working equation for pump power consumption is:

$$(P_{pump})_{AbW} = 0.0292\ q_{AbW} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{hp}$$

3.7.9 Blowdown Rate and Scrubber System Makeup Water Requirements

- Purpose and limitations -- Scrubber system blowdown rates and makeup water requirements must be calculated to estimate disposal costs and overall water costs for facility operation. The accuracy of these calculations is predicated on the applicability of numerous assumptions listed in preceding sections and, to a lesser extent, the assumptions listed below.

- Applicability -- All facilities
- Assumptions and guidelines:
  - Either a venturi scrubber, acid gas absorber, or both are required for all hazardous waste incineration facilities. Otherwise, the "wastes" in question should be suitable for more profitable applications such as boiler fuel.
  - The nominal blowdown rate is 5 percent of the combined quench/venturi scrubber/absorber effluent to the recycle tank
- General relationship:
  - Three separate scrubbing system scenarios are possible based on the assumptions listed above: venturi scrubber only, acid gas absorber only, or venturi scrubber and absorber in series. However, the same general material balance expression can be used in all cases to estimate theoretical scrubber makeup water requirements so long as inapplicable terms are assigned values of zero. Neglecting the caustic feedrate, this general material balance expression is:

    (Scrubber makeup water) + (Quench effluent) + (Venturi scrubber effluent) + (Absorber effluent) = (Venturi scrubber feed) + (Absorber feed) + (Quench feed) + (Blowdown)

  - Because the quench exit gas is saturated, feedrates and effluent discharge rates from both the venturi scrubber and the acid gas absorber are equivalent. Therefore,

    (Scrubber makeup water) + (Quench effluent) = (Quench feed) + (Blowdown)

  - And with a quench feedwater rate two times the theoretical requirement,

    (Scrubber makeup water) = (Quench effluent) + (Blowdown)

-- Finally, a 5 percent blowdown is given by,

(Blowdown) = 0.05[(Quench effluent) + (Venturi scrubber effluent) + (Absorber effluent)]

- Working relationships:

  -- Based on these material balance relationships, the blowdown rate is:

$$F_{BdW} = 0.05[(F_{QW})_{eff} + (F_{VSW})_{eff} + (F_{AbW})_{eff}]$$

$$= \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$q_{BbW} = 0.002\ F_{BdW} = \underline{\hspace{3cm}}\ \text{gpm}$$

  -- The makeup water feedrate is thus:

$$F_{SMW} = (F_{QW})_{eff} + F_{BdW} = \underline{\hspace{3cm}}\ \text{lb/hr}$$

$$q_{SMW} = 0.002\ F_{SMW} = \underline{\hspace{3cm}}\ \text{gpm}$$

3.7.10 Scrubber Makeup Water Pump Power Requirement

- Purpose and limitations -- The following calculations are designed to estimate pump power requirements to transfer scrubber makeup water from the plant water source to the scrubber system recycle loop. Limitations in the accuracy of these calculations are predicated on the applicability of the material balance calculations presented throughout Section 3.7.

- Applicability -- All facilities

- Assumptions:

  -- Booster pump discharge pressure is 30 psig

  -- Overall pump/motor efficiency is 50 percent

- Working relationship -- Based on these assumptions and the general expression for pump power consumption:

$$(P_{pump})_{SMW} = 0.035\ q_{SMW} = \underline{\hspace{4cm}}\text{hp}$$

3.8 FLUE GAS HANDLING EQUIPMENT (ID FAN) OPERATION

- Purpose and limitations -- ID fan power requirements constitute a major operating cost for most facilities. The calculations presented below are based on standard engineering equations, so significant inaccuracies should not be introduced in this section.

However, these power calculations are predicated on numerous assumptions through Section 3, so the results may not be representative for specific designs. However, the results should be representative for typical hazardous waste incineration facilities.

- Applicability -- All facilities, since balanced or negative draft operation is assumed for all cases

- Assumptions:

  -- Either a single ID fan, or two ID fans in series, are used to create draft through the (optional) waste heat boiler, quench, and scrubber system, and to maintain slight negative pressure in the incinerator (≤1-in. W.C.)

  -- Pressure drops through the incinerator, waste heat boiler, quench, and absorber are 4-in. W.C., 4-in. W.C., 1-in. W.C., and 7-in. W.C., respectively

  -- Pressure drop across the venturi scrubber may range from 10- to 100-in. W.C., as discussed in Section 3.7.4

  -- Resistance to flow across dampers and ductwork is negligible

  -- Overall fan/motor efficiency is 60 percent

  -- Gas temperature at the fan inlet is the saturation temperature, previously calculated, with absolute pressure depending on the upstream equipment configurations described in Section 3.7

- General relationship:

  -- The general fan power expression is:

$$\text{Power, hp} = 1.57 \times 10^{-4}\,(q_{TG},\ \text{scfm})\,\frac{(T,\ {}^{o}F+460)}{520}$$

$$\times \left(\frac{14.696}{\text{Absolute pressure, psia}}\right)$$

$$\times \frac{(\text{System pressure drop, in. W.C.})}{(\text{Overall fractional efficiency})}$$

- Working relationships:

  -- System pressure drop versus upstream equipment configuration relationships are shown in Table 25

TABLE 25. SYSTEM PRESSURE DROP VERSUS UPSTREAM EQUIPMENT CONFIGURATION

Case no.	Upstream equipment configuration	ΔP_{sys} (in. W.C.)
1	Quench/venturi scrubber	$6 + \Delta P_{VS}$
2	Quench/absorber	13
3	Quench/venturi/absorber	$13 + \Delta P_{VS}$
4	WHB/quench/venturi	$10 + \Delta P_{VS}$
5	WHB/quench/absorber	17
6	WHB/quench/venturi/absorber	$17 + \Delta P_{VS}$

-- Based on the required equipment configuration,

ΔP_{sys} = ___________ in. W.C.

-- Fan power requirements are then given by:

$$P_{fan} = 2.62 \times 10^{-4} (q_{TG})_{sat} \left(\frac{T_{sat} + 460}{520}\right) \times \left(\frac{14.696}{14.696 - \Delta P_{sys}/27.72}\right)\left(\Delta P_{sys}\right)$$

= ___________ hp

SECTION 4

CAPITAL COST ESTIMATION

4.1 OVERVIEW

Two bottom-line capital cost totals are of paramount importance for the hazardous waste incineration facility owner/operator: (1) the depreciable fixed capital investment and (2) the total capital investment. The significance of the total capital investment is obvious -- this is frequently the criterion used to determine whether incinerator or some other method of waste disposal is used. Even if operating costs are lower for incineration than secure landfilling in another state hundreds of miles away, landfilling may seem to be the only feasible option for the plant owner if the capital for incineration facility construction cannot be obtained. This is particularly true for small waste generators. Even large chemical firms, capable of funding construction through internal revenues, consider all alternatives before spending millions on a waste disposal facility when this money could be used to finance production plant expansion. Thus, total capital investment is an important consideration when comparing the costs for incineration to the costs for other waste disposal options, even though total capital investment does not appear directly in the unit disposal cost calculation.

The capital cost figure that directly impacts unit disposal cost is the depreciable fixed capital investment. This is the total capital cost that can be depreciated for income tax purposes, thereby contributing to the annual facility operating cost in an accounting sense.

Figure 15 shows a breakdown of the depreciable and nondepreciable cost elements. As indicated here, the depreciable fixed capital investment includes direct costs for site development, equipment purchase, and installation; as well as indirect costs for engineering, administrative tasks such as permitting, construction overhead and fee, and contingencies. Land is also part of the overall fixed capital investment, however, costs for land purchase are not depreciable. Other cost elements that contribute to the total capital investment, but not to fixed capital, include startup, trial burns, and working capital.

The remainder of this chapter is divided into four primary sections, based on the categorical cost groupings listed above. Section 4.2 addresses the direct costs for site development; front-end storage and handling equipment and ancillary structures; and integrated incineration systems.

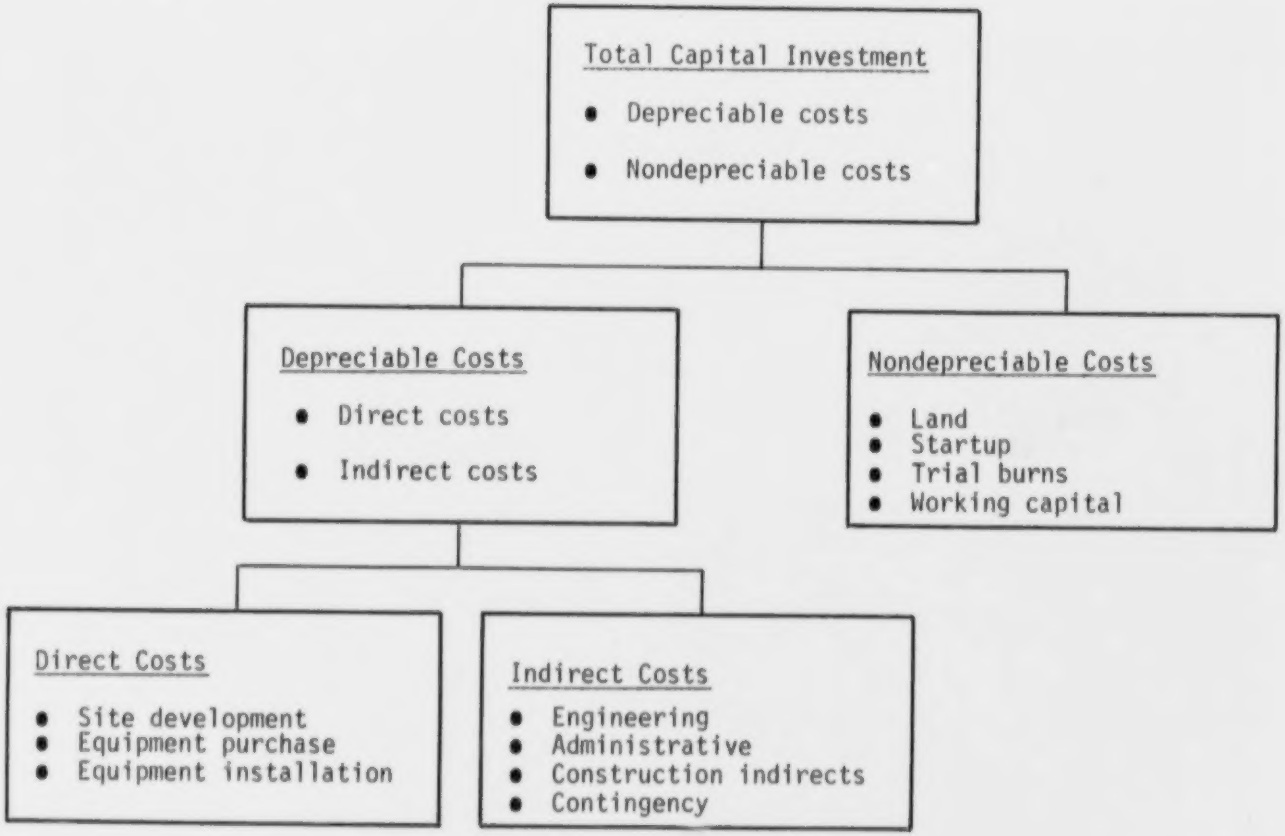

Total Capital Investment
• Depreciable costs
• Nondepreciable costs
Depreciable Costs
• Direct costs
• Indirect costs
Nondepreciable Costs
• Land
• Startup
• Trial burns
• Working capital
Direct Costs
• Site development
• Equipment purchase
• Equipment installation
Indirect Costs
• Engineering
• Administrative
• Construction indirects
• Contingency

Figure 15. Breakdown of total capital investment.

The cost estimates for site development and front-end equipment and auxiliaries are based on (1) input data from Section 2 of this report, (2) the engineering assumptions and design calculations presented in Section 3, and (3) vendor/contractor estimates for the cost of individual equipment items and construction actitivies. Component-by-component cost estimating is needed for the storage and handling system (i.e., the front-end plant) because so much variation can exist between facilities of similar capacity, and because each type of equipment is frequently supplied by a different vendor.

Conversely, incineration systems are usually designed and the equipment provided by only one to three different vendors. In turnkey situations, a single vendor will take responsibility for providing the combustion, heat recovery, and air pollution control subsystems. In other situations, it is common practice for one vendor to supply the incinerator and all necessary auxiliaries, another vendor to supply the waste heat boiler with necessary trim, and a third vendor to supply the air pollution control and flue gas handling subsystem. Therefore, when estimating the costs for incineration systems, it is unnecessary to cost out each separate equipment item. Reasonably accurate (±20 to ±30 percent) estimates can be obtained from vendors for complete subsystems based on the input data specified in Section 2. This approach was used for this study.

Unlike the costs for process equipment and ancillary structures, indirect costs are estimated in Section 4.3 as percentages of the total direct cost. This is in line with normal cost estimating practices where ±30 to 40 percent accuracy is sufficient. Other nondepreciable capital requirements are estimated in Section 4.4 using direct costing methods, factored methods, or a combination of both.

Section 4.5 summarizes these cost elements to provide depreciable fixed capital and total capital investment estimates, which are the cost figures required for the subsequent analyses presented in Sections 5 and 6.

Costs presented in all subsections are representative of the mid-1982 to early-1983 timeframe.

4.2 DIRECT COSTS

4.2.1 Site Development

Basis

The site development activities required for hazardous waste incineration facilities are described in Section 3. The approximate percentages that these activities contribute to the total site development cost are shown in Table 26.

TABLE 26. TYPICAL BREAKDOWN OF SITE DEVELOPMENT COSTS

Activity	Range of site development component costs (percent of total)
Temporary facilities	1.9 to 2.1
Permits, bonds, and fees	1.8 to 2.0
Survey and grade sheet	1.8 to 2.0
Clear and grub, grade, fine grade, compact	3.5 to 4.0
Access road	23 to 37
Crushed rock	15 to 17
Storm drainage	9 to 10
Landscaping	10 to 11
Area lights	3.6 to 9.5
Sanitary sewer	9 to 10
Chain-link fence	3.9 to 4.1
Storage area dike	6.2 to 12

Costs

Total site development cost (excluding construction indirects) versus capacity and facility type are shown in Figure 16. These costs are based on subcontractor estimates. From Figure 16,

C_{SD} = \$____________

4.2.2 Front-End Storage/Handling Equipment and Ancillary Structures

Capital costs for the front-end plant are presented by component type in the following sections.

4.2.2.1 Tanks

Basis

Installed costs for liquid waste, no. 2 fuel oil, and caustic soda solution tanks are presented in Table 27. These costs include subcontractor-estimated purchased costs, plus allowances for freight and installation.

Liquid waste tanks are aboveground, vertical, conical roof, top fill/bottom discharge design of carbon steel construction with concrete support pads. Tanks are equipped for agitation, heating, nitrogen blanketing, and flame arrest.

Fuel oil tanks are similar, except that agitation and heating are not provided.

Caustic soda solution tanks are not nitrogen blanketing nor equipped with flame arresters, but heating and agitation are provided.

Allowances for freight and installation are 5 percent and 30 percent (Reference 7) of the purchased cost, respectively. Obviously, these costs can vary depending on site-specific factors.

Total Installed Cost

The total cost for tanks is determined by multiplying the number of tanks of a given type (N_i) by the installed cost per tank for that type (C_i).

$$\begin{aligned} C_{tank} = {} & N_{HT}\,C_{HT} + N_{ST5}\,C_{ST5} + N_{ST10}\,C_{ST10} + N_{ST20}\,C_{ST20} + N_{BT}\,C_{BT} \\ & + N_{FO5}\,C_{FO5} + N_{FO10}\,C_{FO10} + N_{FO20}\,C_{FO20} + N_{CSS5}\,C_{CSS5} \\ & + N_{CSS10}\,C_{CSS10} + N_{CSS20}\,C_{CSS20} = \$\_\_\_\_\_\_\_\_\_\_ \end{aligned}$$

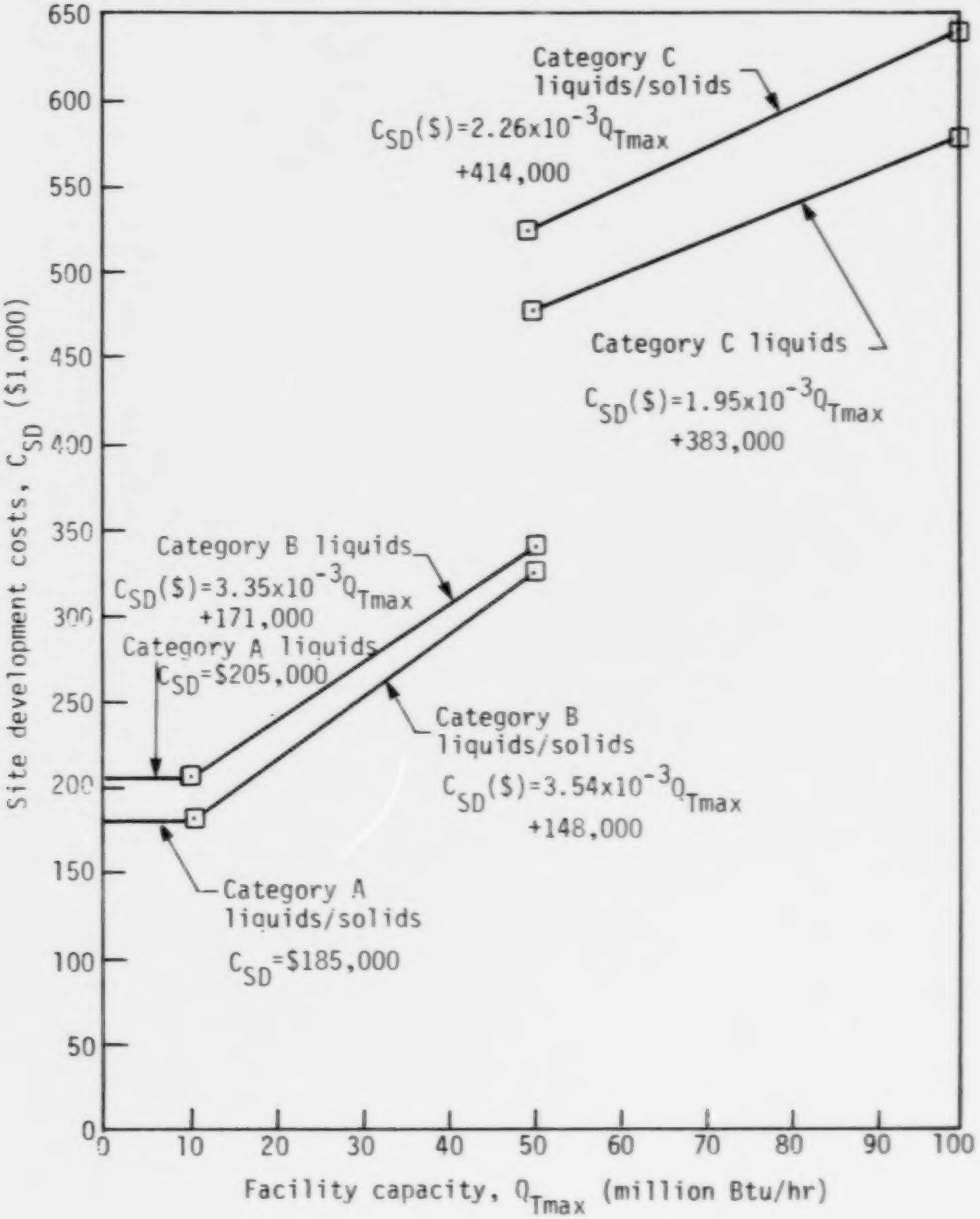


Figure 16. Site development costs (December 1982).

TABLE 27. INSTALLED COSTS OF TANKS (DECEMBER 1982)

Tank type	Tank cost designation	Capacity (gal)	Installed cost (dollars)
Holding	C_{HT}	5,000	34,000
Storage	C_{ST5}	5,000	34,000
Storage	C_{ST10}	10,000	46,000
Storage	C_{ST20}	20,000	61,000
Blending	C_{BT}	10,000	46,000
Fuel oil	C_{FO5}	5,000	21,000
Fuel oil	C_{FO10}	10,000	30,000
Fuel oil	C_{FO20}	20,000	44,000
Caustic soda solution	C_{CSS5}	5,000	25,000
Caustic soda solution	C_{CSS10}	10,000	34,000
Caustic soda solution	C_{CSS20}	20,000	47,000

4.2.2.2 Pumps

Basis

Gear pumps of standard carbon steel construction are assumed for all applications except slurry (WPS) feeding. Moyno pumps are assumed for this application.

Individual costs for pumps include motors, starters, mounting, and wiring.

Installed costs for liquid waste feed pumps, $(C_{pump})_{WCL}$ and $(C_{pump})_{WNL}$, are determined from Figure 17, based on the $(q_{pump})_{WCL}$ and $(q_{pump})_{WNL}$ capacities estimated in Section 3.3.2.1.

Installed costs for slurry pumps, $(C_{pump})_{WPS}$, are determined from Figure 18, based on the $(q_{pump})_{WPS}$ capacity estimated in Section 3.3.2.1.

Installed costs for waste transfer pumps in category C facilities, based on the assumptions presented in Section 3.3.2.2, are as follows:

$(C_{pump})_{UL} = \$4,200$

$(C_{pump})_{HT/ST} = \$4,200$

$(C_{pump})_{ST/BT} = \$2,600$

Installed costs for fuel oil feed pumps are determined from Figure 19, based on the $(q_{pump})_{FO}$ capacity estimated in Section 3.4.11.

Finally, installed costs for caustic soda solution feed pumps are determined from Figure 20, based on the $(q_{pump})_{CSS}$ capacity estimated in Section 3.7.

All costs are based on vendor estimates.

Total Installed Cost

The total cost for pumps is determined by multiplying the number of pumps for a given application, $(N_{pump})_i$, by the unit cost for that type of pump, $(C_{pump})_i$.

$$\begin{aligned} C_{pump} = {} & (N_{pump})_{WCL} (C_{pump})_{WCL} + (N_{pump})_{WNL} (C_{pump})_{WNL} \\ & + (N_{pump})_{WPS} (C_{pump})_{WPS} + (N_{pump})_{UL} (C_{pump})_{UL} \\ & + (N_{pump})_{HT/ST} (C_{pump})_{HT/ST} + (N_{pump})_{ST/BT} (C_{pump})_{ST/BT} \\ & + (N_{pump})_{FO} (C_{pump})_{FO} + (N_{pump})_{CSS} (C_{pump})_{CSS} \\ = {} & \$\rule{3cm}{0.4pt} \end{aligned}$$

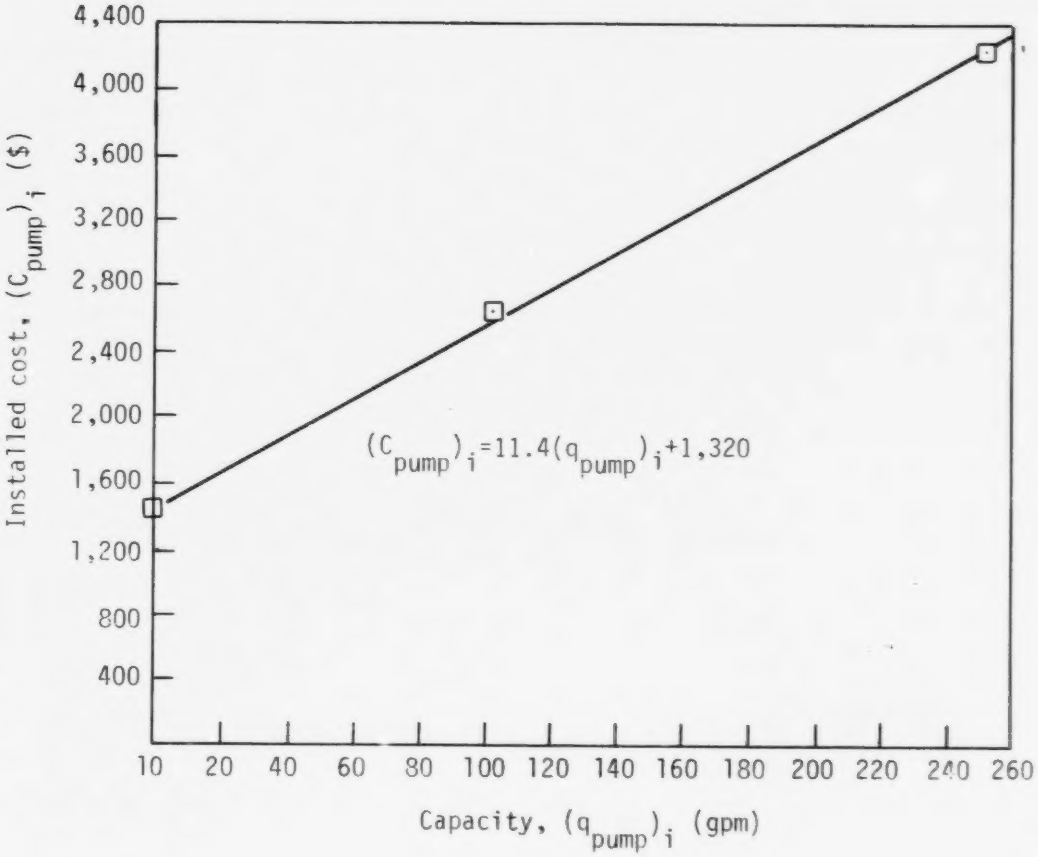


Figure 17. Installed cost of liquid waste feed pumps (December 1982).

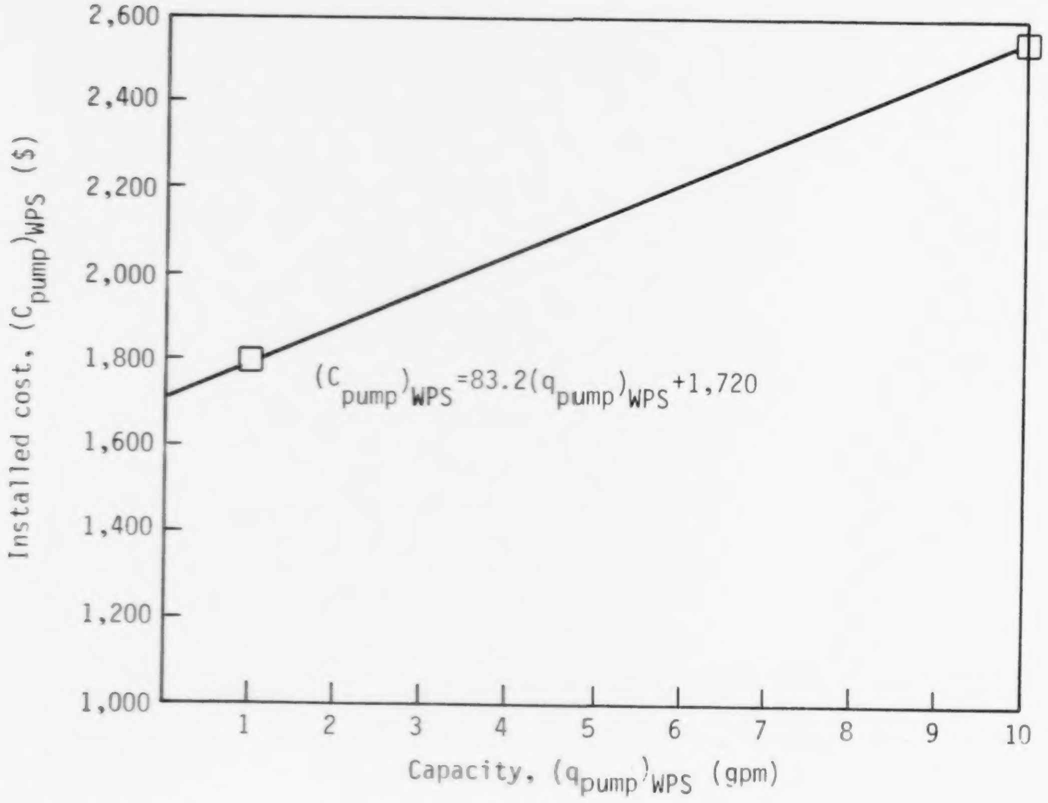


Figure 18. Installed cost of slurry pumps (December 1982).

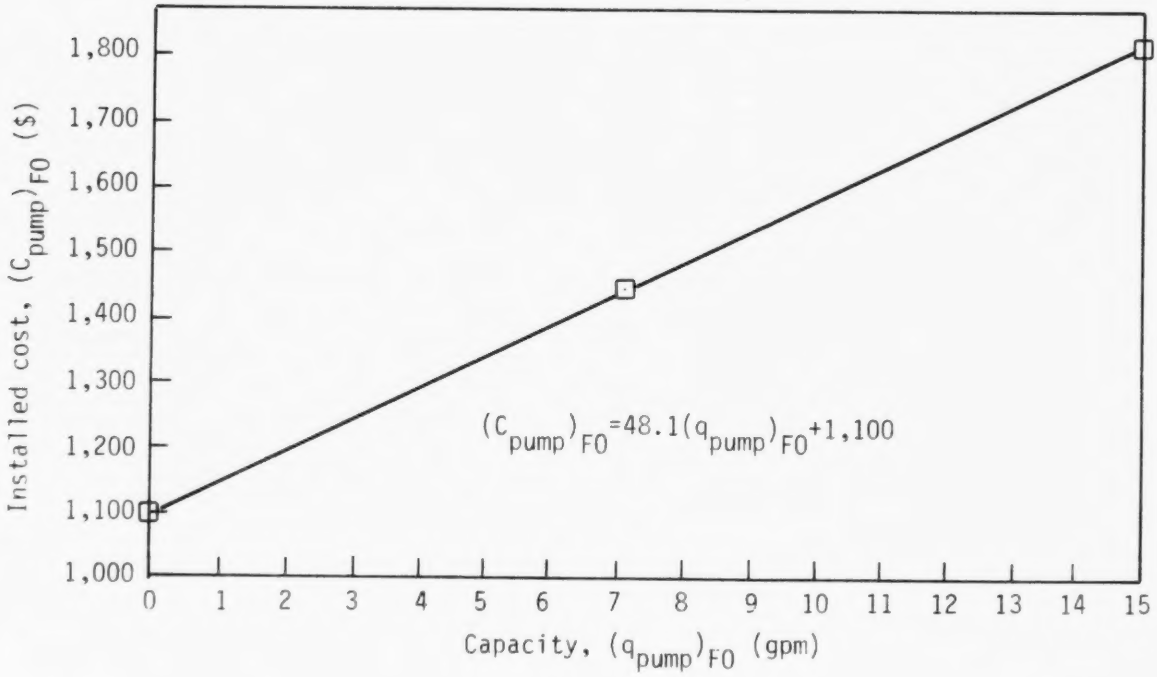


Figure 19. Installed cost of fuel oil feed pumps (December 1982).

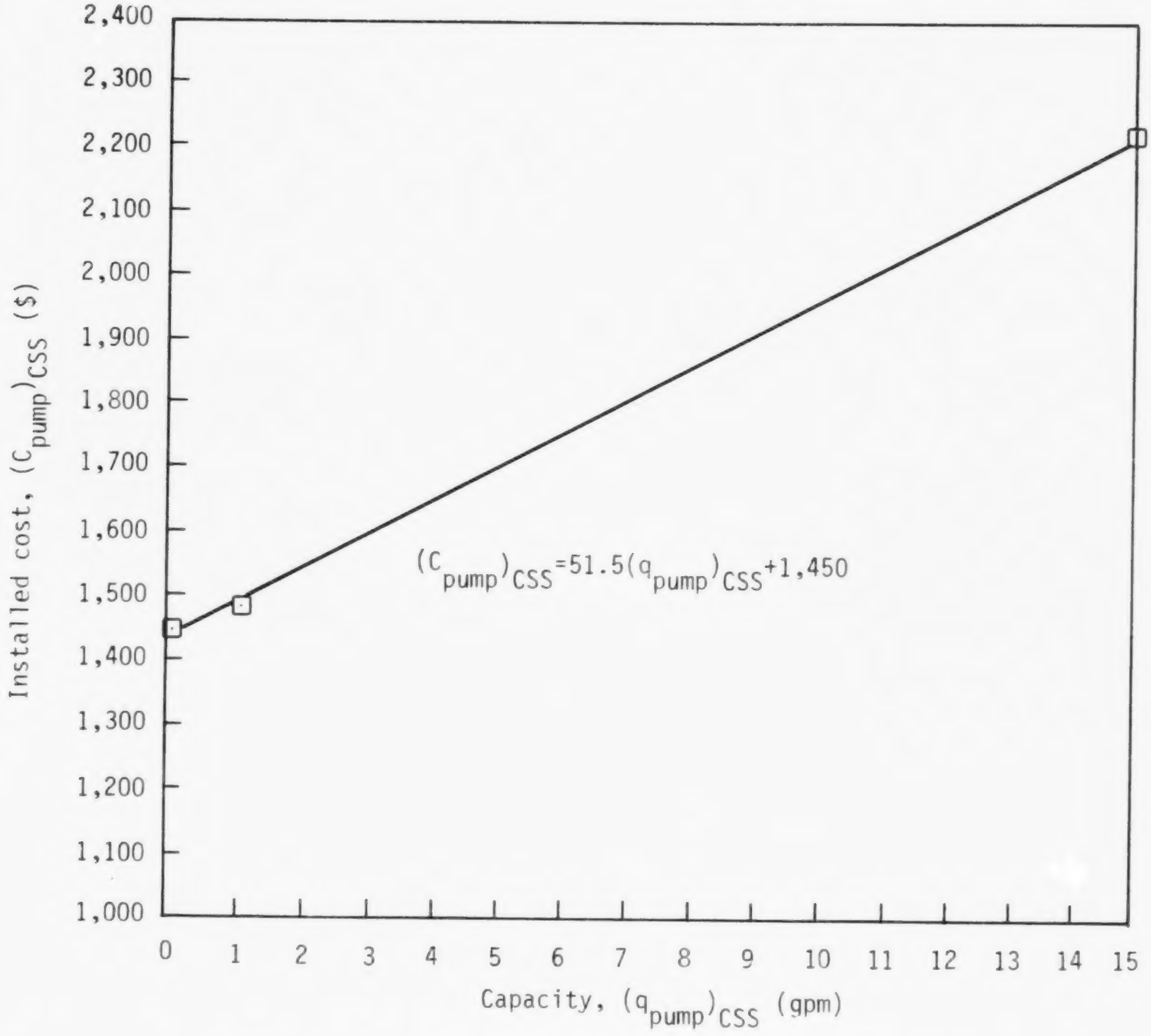


Figure 20. Installed cost of caustic soda solution pumps (December 1982).

4.2.2.3 Piping

Basis

Nominal piping diameters are either 1, 2, 3, or 4 in., depending on the flow in various segments of the front-end plant.

Dollars per linear foot piping cost estimates are based on schedule 40, carbon steel pipe with allowances for valves, fittings, insulation, hangers, and installation labor. These unit costs versus nominal diameters, (D_{pipe}) are shown in Table 28.

The costs are based on subcontractor estimates.

Total Installed Cost

The total cost for piping is determined by multiplying the length of pipe needed for a given application, $(L_{pipe})_i$, by the appropriate unit cost, $(UC)_i$.

$$\begin{aligned} C_{pipe} &= (L_{pipe})_{WCL}\,(UC)_{WCL} + (L_{pipe})_{WNL}\,(UC)_{WNL} \\ &\quad + (L_{pipe})_{WPS}\,(UC)_{WPS} + (L_{pipe})_{UL}\,(UC)_{UL} \\ &\quad + (L_{pipe})_{HT/ST}\,(UC)_{HT/ST} + (L_{pipe})_{ST/BT}\,(UC)_{ST/BT} \\ &\quad + (L_{pipe})_{FO}\,(UC)_{FO} + (L_{pipe})_{CSS}\,(UC)_{CSS} + (L_{pipe})_{LN}\,(UC)_{LN} \\ &= \$\underline{\hspace{2cm}} \end{aligned}$$

TABLE 28. UNIT INSTALLED COSTS FOR PIPING (DECEMBER 1982)

Nominal pipe diameter D_{pipe} (in.)	Unit installed cost, $(UC)_i$ (\$/ft)
1	21.95
2	29.30
3	39.30
4	49.00

4.2.2.4 Carts

Basis

All carts are of steel construction with straight sides and are equipped with hydraulic dumping mechanisms.

Assuming that 16 carts are purchased, costs for individual carts versus capacity (M_{cart}) are shown in Table 29.

These costs are based on subcontractor estimates.

Total Cost

The total cost for carts is equal to 16 times the appropriate unit cost, which is based on the M_{cart} value determined in Section 3.3.4.

$$C_{cart} = 16(UC)_{cart} = \$\_\_\_\_\_\_\_\_$$

4.2.2.5 Vehicles

Basis

Two types of vehicles are used to transport solid wastes in incineration facilities, one handles carts full of bulk solids and the other moves drums around on pallets.

TABLE 29. COST OF CARTS FOR SOLID WASTE STORAGE AND TRANSFER (DECEMBER 1982

Cart capacity M_{cart} (yd^3)	Unit cost, $(UC)_{cart}$ (\$)
0.5	3,500
1	4,700
2	9,000
3	14,000
4	16,000
5	20,000

For category A and B facilities, forklift trucks equipped with cart dumping rotators are assumed to be the vehicles of choice. A typical mid-range price for this type of vehicle is $30,000.

In category C facilities, lift trucks capable of handling four drums of waste on a 48-in.-by-48-in. pallet are the vehicles of choice. This type of vehicle typically costs $18,000.

As assumed in Section 3.3.5, two vehicles are needed for category A and B facilities and four for category C facilities.

Total Cost

Based on these assumptions, total costs for vehicles are:

C_{veh} = $60,000 for category A and B facilities

C_{veh} = $72,000 for category C facilities

4.2.2.6 Bulk Solid Waste Conveyors

Basis

Bulk solids conveying systems for category C facilities include an underdrag screw conveyor, a bucket elevator, and an elevated, enclosed belt conveyor as described in Section 3.3.6.

Screw conveyor lengths are 50 ft for smaller category C facilities and 75 ft for larger facilities, as quantified in Section 3.3.6.

Belt conveyor lengths are 50 ft, and bucket elevator heights are 25 ft.

Solids density is approximately 50 lb/ft^3.

Weight capacities are determined by the bulk solids feedrate, but should not exceed 2 to 4 tons/hr. Installed costs do not vary significantly for solids handling equipment in this small size range. Representative costs are shown in Table 30.

The design features of these equipment items and auxiliaries on which the costs are based include:

- Bucket elevator:
    - Explosion-proof drive
    - 25-ft discharge height
    - Continuous buckets

TABLE 30. INSTALLED COSTS OF BULK SOLID WASTE CONVEYING EQUIPMENT (DECEMBER 1982)

Equipment item	Installed cost ($)
Screw conveyor, 50 ft	10,500
Screw conveyor, 75 ft	15,700
Bucket elevator, 25 ft	21,900
Belt conveyor, 50 ft	26,300

  - 1-hp drive
  - 2.5 tons/hr @ 50 lb/ft^3
  - Ladder and platform included
- Belt conveyor:
  - 50-ft section
  - Covered
  - Explosion-proof motor
  - 4 tons/hr @ 50 lb/ft^3
  - 2-hp drive
- Screw conveyor:
  - 2.5 tons/hr @ 50 lb/ft^3
  - 3-hp drive
  - 9-in. diameter flights
  - Explosion-proof drive

Purchased costs are based on vendor estimates. Freight and installation are estimated as 100 percent of the purchased costs, based on subcontractor estimation.

Total Installed Cost

The total cost for a bulk solids conveying system is given by:

$$(C_{conv})_{WBS} = (\text{Screw conveyor cost}) + (\text{Bucket elevator cost}) + (\text{Belt conveyor cost})$$

For smaller category C facilities (50 to 75 million Btu/hr):

$$(C_{conv})_{WBS} = \$58,700$$

For the larger facilities (75 to 100 million Btu/hr):

$$(C_{conv})_{WBS} = \$63,900$$

4.2.2.7 Bulk Solid Waste Feeders

Ram feeders are normally provided as part of rotary kiln or multiple chamber, hearth-type incineration systems. Therefore, the cost for feeders is included in the incineration system costs presented in Sections 4.2.4 and 4.2.5.

4.2.2.8 Drum Elevators and Conveyors

Basis

Section 3.3.8 describes the roller conveyor and drum elevator system configuration used for containerized waste feeding in category C facilities.

Drum elevator height is 25 ft. Operating capacity requirements are determined by the weight of a single drum, approximately 450 lb, for all systems.

Installed costs for drum elevators and auxiliaries are approximately $35,000, based on vendor and subcontractor estimates. Design features include:

- 25-ft discharge height
- 450-lb drum (55 gal)
- Vertical and horizontal lift
- Explosion-proof drive (1 hp)

Roller conveyors lengths, $(L_{conv})_{WCS}$, are roughly proportional to the number of drums/hr, N_{WCS}, fed to the incinerator, as described and quantified Section 3.3.8.

Installed costs for 50-ft roller conveyor spans, including auxiliaries, are $18,000, based on vendor and subcontractor estimates. Design features include:

- Explosion-proof motors, 2 hp per 50-ft section
- Live roller
- Feed from forklift
- Chain driven
- 1 ft off floor

All costs are in December 1982 dollars.

Total Installed Cost

The total cost for a drum conveying system is the sum of the drum elevator and roller conveyor costs. Based on the costs presented above:

$$(C_{conv})_{WCS} = \$35{,}000 + \frac{(L_{conv})_{WCS}}{50}(\$18{,}000)$$

$$= \$\underline{\hspace{3cm}}$$

4.2.2.9 Compressors

Basis

A compressor is needed in all facilities to provide atomizing air for liquid waste burners.

Compressor discharge pressure is 100 psig.

Installed costs for compressors versus capacity in scfm, $(q_{air})_{comp}$, are shown in Figure 21. The data points represent individual subcontractor estimates.

These costs are based on the following design features:

- Air cooled
- Electric
- Basemounted
- Rotary screw

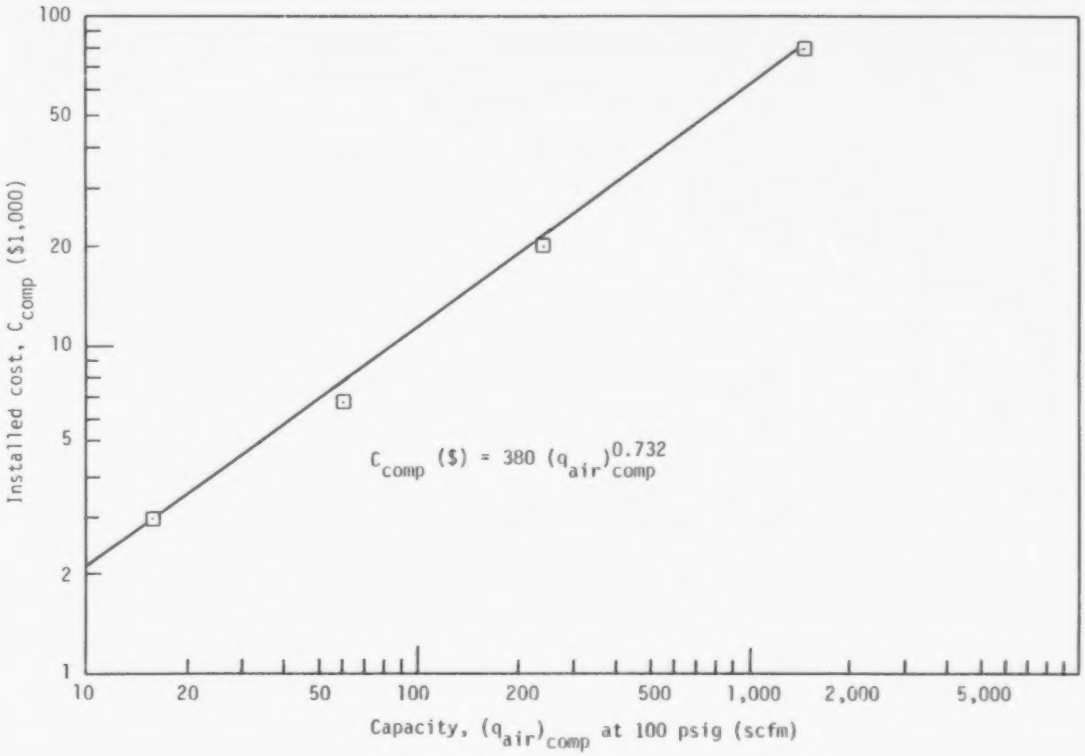


Figure 21. Air compressor (100 psig) installed cost (December 1982).

Installed Cost

From Figure 21 and the $(q_{air})_{comp}$ value calculated in Section 3.3.9:

C_{comp} = \$__________

4.2.2.10 Buildings

Receiving Station Enclosures

Basis

From Section 3.3.10.1, space requirements for liquid waste unloading station enclosures in category C facilities are given by $A_{POS}(ft^2)$.

Construction costs for this type of structure are typically $\$36.00/ft^2$ (late 1982 timeframe). This subcontractor estimate is based on the following construction specifications:

- Prefabricated steel building
- Reinforced concrete slab floor
- Lights
- Doors and windows
- Fire suppression system

Cost

Costs for unloading station enclosures are given by:

$(C_{bldg})_{UL} = (A_{POS}, ft^2)(\$36.00/ft^2)$

= \$__________

Bulk Solid Waste Storage Enclosures

Basis

In category A and B facilities, bulk solid wastes are stored in carts within warehouses. Construction costs for this type of warehouse are typically $\$37.15/ft^2$ (late 1982 timeframe), based on the following subcontractor design assumptions:

- Prefabricated steel building
- Reinforced concrete slab floor

- Doors and windows
- Lights
- Loading dock
- Fire suppression system

From Section 3.3.10.2, approximate space requirements for these cart storage warehouses are given by $A_{WBS}(ft^2)$.

In category C facilities, bulk solids are stored in pits enclosed by warehouses. Floor space requirements for these facilities are also given by A_{WBS}.

Total construction costs for these two warehouse sizes, including the pits, is $45.55/$ft^2$ (late 1982 timeframe). This cost is based on the same subcontractor design assumptions as the category A and B facilities, except for the storage pit.

Cost

For category A and B facilities:

$$(C_{bldg})_{WBS} = (A_{WBS},\ ft^2)(\$37.15/ft^2)$$

$$= \$\_\_\_\_\_\_\_\_\_\_$$

For category C facilities:

$$(C_{bldg})_{WBS} = (A_{WBS},\ ft^2)\ (\$45.55/ft^2) = \$\_\_\_\_\_\_\_\_\_\_$$

Drum Storage Enclosures

Basis

Assumptions concerning warehouse sizing for drummed waste storage are presented in Section 3.3.10.3.

Total warehouse space is given by $A_{WCS}(ft^2)$, also described in Section 3.3.10.3.

Typical construction costs for this type of warehouse are $36.00/$ft^2$ (late 1982 timeframe), based on the following subcontractor design assumptions:

- Prefabricated steel building
- Lights

- Doors and windows
- Reinforced concrete slab floor
- Fire suppression system

Cost

Total cost for warehouse construction is given by:

$$(C_{bldg})_{WCS} = (A_{WCS},\ ft^2)\ (\$36.00/ft^2)$$

$$= \$\_\_\_\_\_\_\_\_\_\_$$

Compressor Enclosures

Basis

As indicated in Section 3.3.10.4, the space requirement for compressor housing in all facilities is $A_{comp} = 400\ ft^2$.

Typical construction costs for these structures are $\$15.75/ft^2$ in late 1982 dollars. This cost is based on the following subcontractor design assumptions:

- Prefabricated steel building
- Reinforced concrete slab floor
- Lights
- Doors and windows

Cost

For all facilities:

$$(C_{bldg})_{comp} = (A_{comp},\ ft^2)\ (\$15.75/ft^2) = \$6,300$$

Control Room and Auxiliaries

Basis

For category A and B facilities, a 900-ft^2 (30 ft by 30 ft) control room is provided, thus, $A_{CR} = 900\ ft^2$. This includes space for the instrumentation and control panel and limited space for operator occupation.

A typical construction cost for this structure (excluding the controls) is \$42/ft^2 in late 1982 dollars, based on the following subcontractor design assumptions:

- Concrete floor (tile)
- Insulation
- Doors and windows
- Bathroom
- Lights
- HVAC

In category C facilities, a 3,000-ft^2 (30 ft by 100 ft) building is needed for control room, laboratory, and office space, therefore, A_{CR} = 3,000 ft^2. Including internal furnishings and lab equipment, a typical cost for this type of building is \$200,000, also in late 1982 dollars. This is based on the following assumptions:

- Concrete block construction
- Bathroom
- HVAC
- Lights
- Concrete floor (tile)
- Insulation
- Doors and windows
- Laboratory equipped with gas chromatograph, infrared spectrometer, bomb calorimeter, wet chemical tests for chlorine, hoods, miscellaneous labware, storage facilities, and tests for determining waste mixing and storage considerations
- Office equipment including desks, file cabinets, chairs, tables, and miscellaenous supplies

Cost

For category A and B facilities:

$$(C_{bldg})_{CR} = (A_{CR}, ft^2)\ (\$42/ft) = \$37,800$$

For category C facilities:

$$(C_{bldg})_{CR} = \$200,000$$

4.2.3 Liquid Injection Incineration Systems

As defined here, a liquid injection incineration system includes the incinerator and auxiliaries, waste heat boiler (optional), and scrubbing/flue gas handling system. The estimated purchase prices for these subsystems are presented in the following three sections, followed by a total installed cost summary in Section 4.2.3.4. All costs are for the May-August 1982 time period, and are based on vendor estimates.

4.2.3.1 Liquid Injection Incinerators

Basis

Many different liquid incinerator designs are commercially available, some of which are significantly more expensive than others. Factors that affect the purchase price, other than capacity, include:

- Design residence time
- Design temperature, which impacts refractory type and thickness
- Acid or salt environment, which also impacts refractory selection
- Number, type, and capacity of fuel/waste burners
- Control system sophistication
- Degree to which the unit is prepackaged
- Vendor markup for engineering design and fee

Given the accuracy requirements of this study (±30 percent), two basic designs that reflect current industry practice are sufficient for cost versus capacity estimating purposes.

The first type of unit is designed to burn relatively clean liquids (insignificant chlorine or salts) such as light hydrocarbon solvents or oily wastes. Normal operating temperatures seldom exceed 1,800°F, and residence times are short -- 0.3 to 0.5 sec. The basic components of the system are:

- Cylindrical steel shell, horizontally aligned
- 2,700°F aluminosilicate castable refractory, 8 to 12 in. thick depending on capacity
- Air-atomizing dual-fluid burner and valve train for waste and fuel oil

- Combustion air blower and accessories
- Complete flame safeguard and combustion control instrumentation

Purchased costs versus capacity for this type of system are given by the lower curve in Figure 22.

The second type of unit is designed to handle the more problematical liquid wastes such as highly chlorinated materials, salty aqueous wastes, and liquified tars -- in addition to the simple hydrocarbon wastes described above. These units are usually designed to accommodate operating temperatures up to 2,200° to 2,400°F. Residence times are nominally 2 sec (1.5 to 2.5 sec). The basic components of this design are:

- Cylindrical, vertical or horizontal steel shell
- 6 to 8 in. of >3,000°F castable or 60 to 80 percent alumina firebrick, backed by insulating castable
- Separate air-atomized guns (or fuel rings) and valve trains for fuel, high-Btu and low-Btu wastes
- Combustion air blower and accessories
- Complete flame safeguard and combustion control instrumentation

Purchased costs versus capacity for this type of unit are given by the upper curve in Figure 22.

Purchase Cost

From the incinerator capacity, Q_{Tmax}, and severity of service specified in Section 2, and Figure 22, the purchase cost is:

C_{LI} = $__________

4.2.3.2 Waste Heat Boilers

Basis

Waste heat boilers are used primarily in category B facilities (10 to 50 million Btu/hr) where the steam can be used in one or more production processes, thus reducing the load in the main plant boiler complex.

Waste heat boiler application in smaller, category A facilities is less likely (although feasible in some cases), and even less likely in commercial category C facilities because there is usually no market for the steam. However, the waste heat boiler cost-versus-capacity curves presented in Figure 23 do encompass likely gas flowrates for category A and smaller category C facilities, as well as category B facilities.

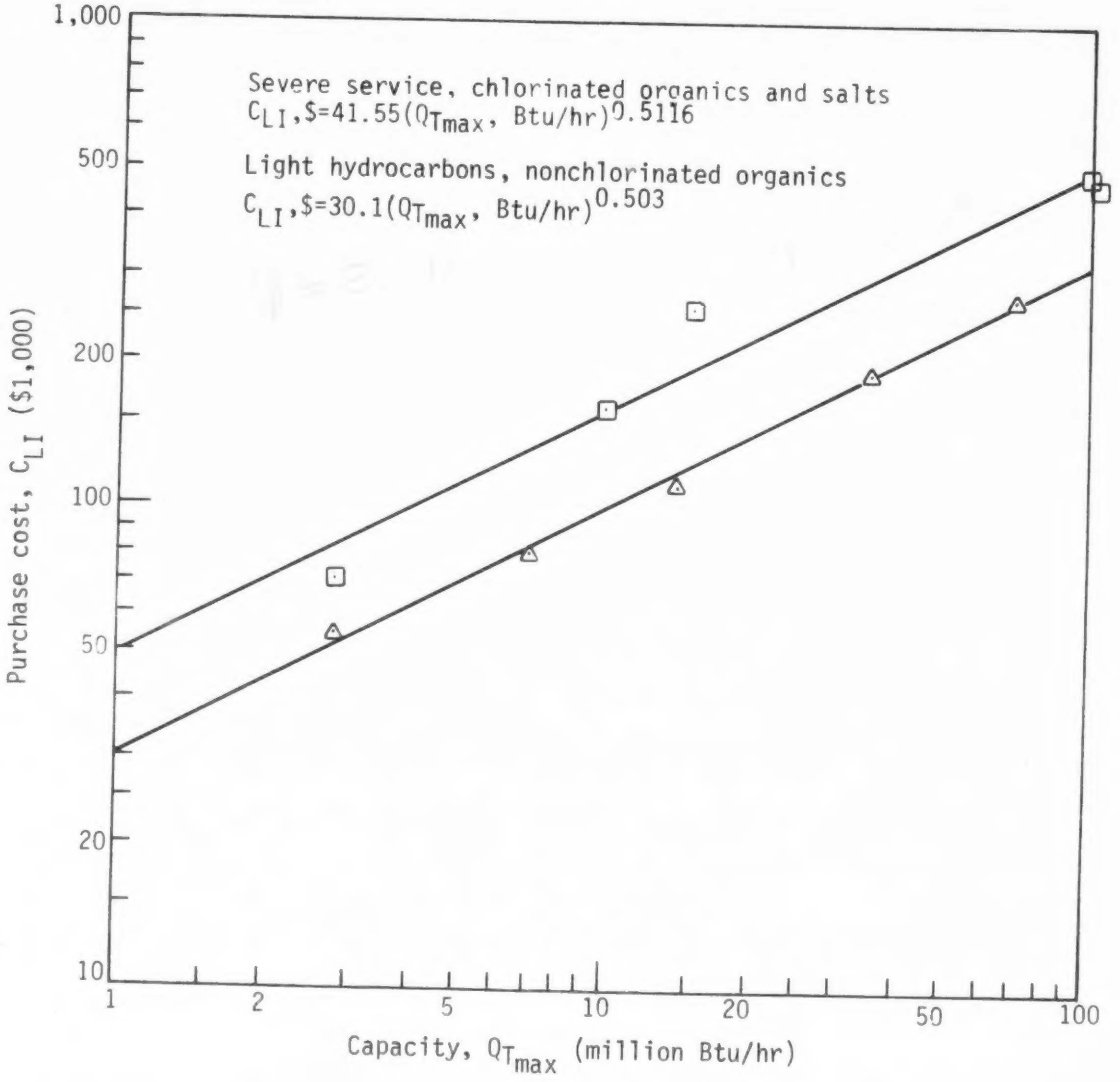


Figure 22. Purchase cost of liquid injection incinerators (May to July 1982).

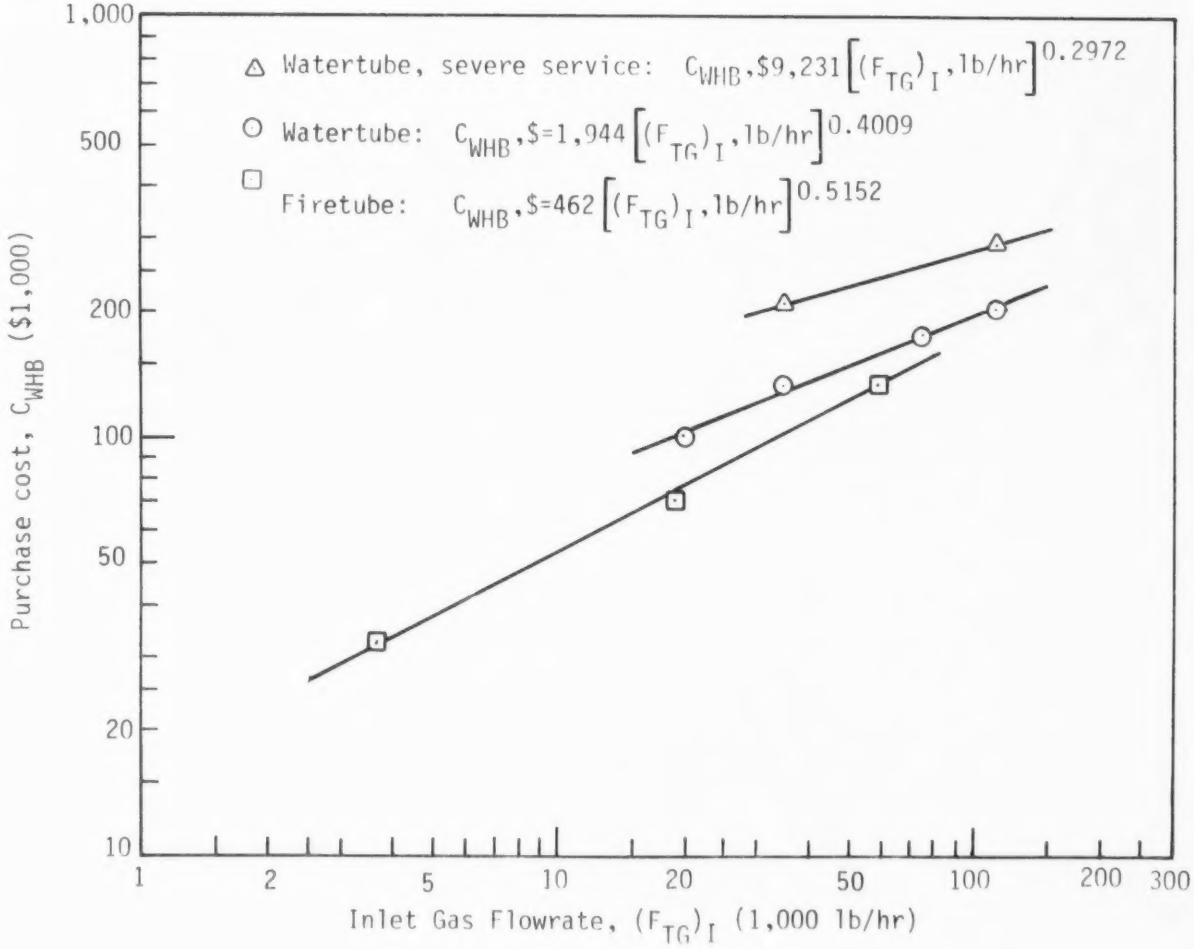


Figure 23. Purchase cost of waste heat boilers (July 1982).

Three separate cost-versus-capacity (gas flowrate) curves are presented in Figure 23. The lower curve is for firetube boilers, preferred in smaller facilities. The middle curve is for watertube boilers of standard design, and the upper curve is for watertube boilers operating in extremely high particulate loading and high acid gas environments.

The costs for all boilers are based on inlet temperatures of 1,800° to 2,200°F, outlet temperatures of approximately 500°F, steam pressures of 150 psig for the firetube boilers, and 150 to 200 psig for the watertube designs.

The costs include the packaged boiler system plus standard trim (feedwater connection and regulator, blowoff valves, etc.), but no platforms, ducting, or control interface with upstream or downstream equipment. These elements are factored into the total system cost in Section 4.2.3.4.

Purchase Cost

Waste heat boiler cost (C_{WHB}) can be determined directly from Figure 23, given (1) the preferred type of waste heat boiler (Section 2), and (2) the mass flowrate of gas at the incinerator exit, $(F_{TG})_I$, calculated in Section 3.4.7. From Figure 23,

C_{WHB} = $____________

4.2.3.3 Scrubbing Systems

Basis

Scrubbing system designs and costs vary considerably from one hazardous waste incineration system to the next, depending on a number of factors. The most important factors, other than capacity (inlet gas flowrate), are:

- Particulate loading and size distribution
- Acid gas scrubbing requirement
- Preferred materials of construction
- Upstream waste heat boiler utilization
- Vendor markup

Therefore, several simplifying assumptions were made to develop the cost versus capacity curves for scrubbing systems shown in Figures 24 and 25. These assumptions (and costs) are based on recommendations from reputable vendors and independent engineering judgment.

Typical scrubbing and flue gas handling systems for hazardous waste incineration facilities include quenches, venturi scrubbers for particulate

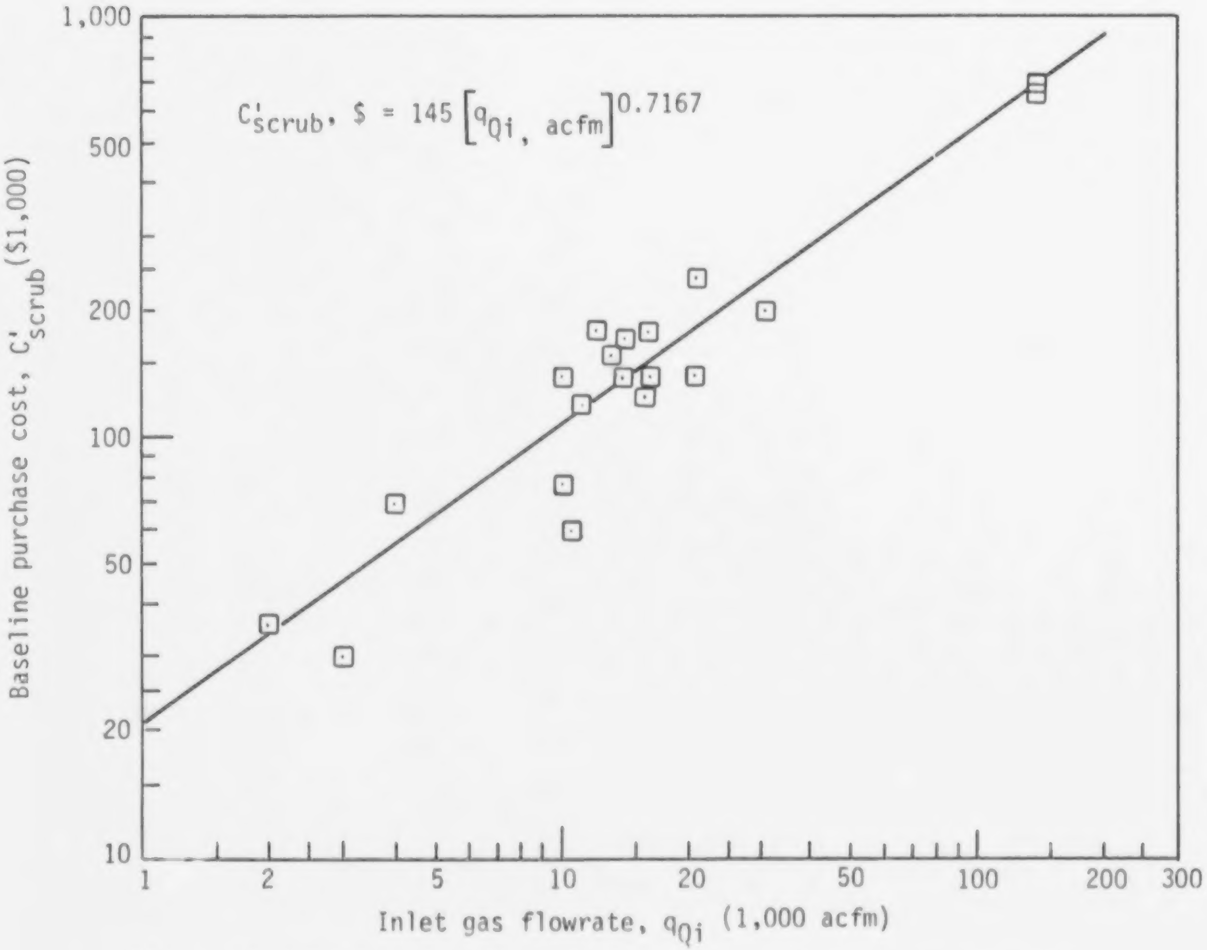


Figure 24. Purchase costs for typical hazardous waste incinerator scrubbing systems receiving 1,800° to 2,200°F gas (July 1982).

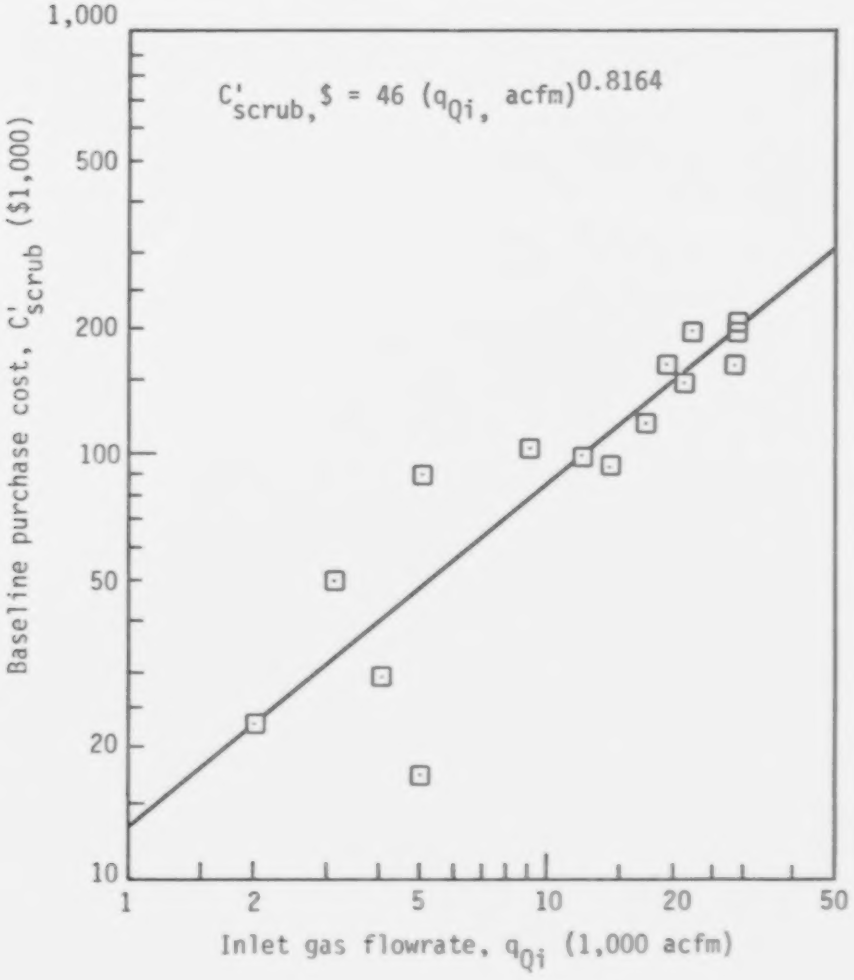


Figure 25. Purchase cost of scrubbing systems receiving 500° to 550°F gas (July 1982).

collection, acid gas absorbers, caustic recycle systems, ID fans, and stacks, plus auxiliaries. For systems receiving hot combustion gas directly from the incinerator (no waste heat boiler), a typical cost breakdown is as follows:

• Quench, venturi, wetted elbow	9 percent
• Cyclonic separator, integral packed tower absorber	30 percent
• Caustic system	17 percent
• ID fan	18 percent
• Stack	10 percent
• Ductwork	3 percent
• Piping	3 percent
• Platform and foundations	4 percent
• Instrumentation and controls	6 percent

Critical-component materials of construction are:

- High nickel alloy quench, venturi throat, and wetted elbow construction
- High-grade, chemically resistant, high-temperature fiberglass resin with a thick fiberglass shell for the cyclonic separator and packed tower
- Polypropylene tower packing
- Inconel or Hastelloy fan wheel with rubber-lined steel housing

The typical system costs shown in Figure 24 are based on a venturi pressure drop requirement of 30-in. W.C., which is also typical. For high pressure drop systems (approximately 100-in. W.C.), the additional costs for the venturi and multiple, high-head fans frequently double the total system cost.

If no venturi scrubber is needed for particulate control, the total system cost is reduced by 15 percent.

If acid gas absorption is not required, the total system cost is reduced by approximately 40 percent.

And finally, if an extremely high venturi pressure drop, but no acid gas absorption, is required, then the total system cost is approximately 20 percent greater than shown in Figure 24.

Figure 25 presents typical costs for scrubbing systems receiving approximately 550°F gas from waste heat boilers. For the same incinerator capacity, this type of system is usually less expensive than the system described above. The same equipment components are needed, however, the quench duty and saturated gas flowrate are reduced by waste heat boiler utilization. Therefore, a smaller quench, venturi scrubber, and acid gas absorption column can be utilized for any given incinerator capacity if a waste heat boiler is employed.

In terms of cost adjustment for high venturi pressure drop, acid gas absorber deletion, or venturi scrubber deletion, the baseline costs presented in Figure 25 can be treated in the same manner as the baseline costs presented in Figure 24.

Purchase Cost

To use Figures 24 and 25, it is necessary to calculate the volumetric gas flowrate at the quench inlet, (q_{Qi}). If no waste heat boiler is utilized,

$$q_{Qi} = (q_{TG})_I \left(\frac{T_{I2} + 460}{520}\right) = \_\_\_\_\_\_\_\_ \text{ acfm}$$

From Figure 24, the baseline scrubbing system cost is:

$$C'_{scrub} = \$\_\_\_\_\_\_\_\_$$

If a waste heat boiler is used, the quench inlet temperature is 550°F, so:

$$q_{Qi} = 1.94\ (q_{TG})_I = \_\_\_\_\_\_\_\_ \text{ acfm}$$

From Figure 25, the baseline scrubbing system cost is:

$$C'_{scrub} = \$\_\_\_\_\_\_\_\_$$

Adjustment factors for the baseline costs are shown in Table 31.

The adjusted scrubbing system purchase cost is then given by:

$$C_{scrub} = (C'_{scrub})\ (CAF) = \$\_\_\_\_\_\_\_\_$$

4.2.3.4 Total Installed Cost for Liquid Injection Incineration Systems

Basis

Total installed cost includes delivery, installation materials, and direct installation labor in addition to the purchased equipment costs derived in the preceding sections.

TABLE 31. COST ADJUSTMENT FACTORS FOR SCRUBBING SYSTEMS

Adjustment from baseline scenario	Cost adjustment factor (CAF)
Extremely high venturi ΔP (100-in. W.C.)	2.0
Same, but no acid gas absorption	1.2
No venturi required	0.85
No absorption system required	0.6

Equipment delivery costs are variable because they depend on the weight and dimension of individual components as well as the distance between the site and the fabrication plant, mode of transportation, etc. However, 5 percent of the FOB cost is a reasonable allowance for delivery charges.

Installation includes all direct material and labor costs to erect the major equipment items, plus plumbing and wiring. These costs can range from 25 to 100 percent of the purchased equipment cost for complete incineration and scrubbing systems. However, 50 percent of the purchased cost is a reasonable average. Lower-percentage installation costs usually reflect considerable prepackaging during fabrication, which, in turn, increases the purchase price. Higher-percentage installation costs usually reflect problems during construction, which are allotted for by contingencies later in this section.

Installation costs for waste heat boilers are usually only 20 to 30 percent of the purchase cost (or less in some cases) due to the extent of prepackaging. For the purposes of this study, however, a 50 percent installation factor is assumed for waste heat boilers as well as incineration and scrubbing systems. This provides a reasonable allowance for controls, platforms, ductwork, and interfacing with upstream and downstream subsystems. These elements are not included in the waste heat boiler costs presented in Figure 23.

Total Installed Cost

Based on these assumptions, the total incineration system cost is given by:

$$C_{TIS} = 1.55(C_{LI} + C_{WHB} + C_{scrub})$$

$$= \$\underline{\hspace{3cm}}$$

4.2.4 Rotary Kiln Incineration Systems

As for the liquid injection incineration systems treated in Section 4.2.3, a rotary kiln system includes the kiln/afterburner and auxiliaries plus waste heat boiler (optional) and scrubbing/flue gas handling system.

4.2.4.1 Rotary Kiln Incinerators

Basis

Rotary kiln incinerators are capable of handling liquid wastes as well as bulk solids and (in larger sizes) drummed wastes. This versatility comes at a higher cost than that required for liquid injection or hearth incinerators. Therefore, it is assumed that rotary kiln systems are designed to handle problem wastes such as chlorinated liquids and sludges, salty wastes, assorted bulk solids and tars, and drums of wastes ($\geq$50 million Btu/hr capacity).

Purchase costs for rotary kiln/afterburner systems designed to handle these types of wastes are presented in Figure 26. These costs are based on vendor estimates and reflect the following design characteristics:

- Stainless steel shell with dual hardened girth gears to resist bowing
- Trunnion roll and drive assemblies, with supports
- Horizontal afterburner integrally connected to kiln breeching
- 70-percent alumina refractory in kiln and afterburner, 9 in. thick
- Ash quench tank and conveyor
- Ram feeder for bulk solids, including hopper, loading ram, hydraulic actuator, and controls
- Feed chute, including double air-lock for drum feeding in larger units
- Air-atomizing dual-fluid burners for high-Btu waste/fuel in kiln and afterburner
- Air-atomizing low-Btu waste guns and slurry lances in kiln feed plate
- Combustion air blower and accessories
- Complete flame safeguard and combustion control instrumentation

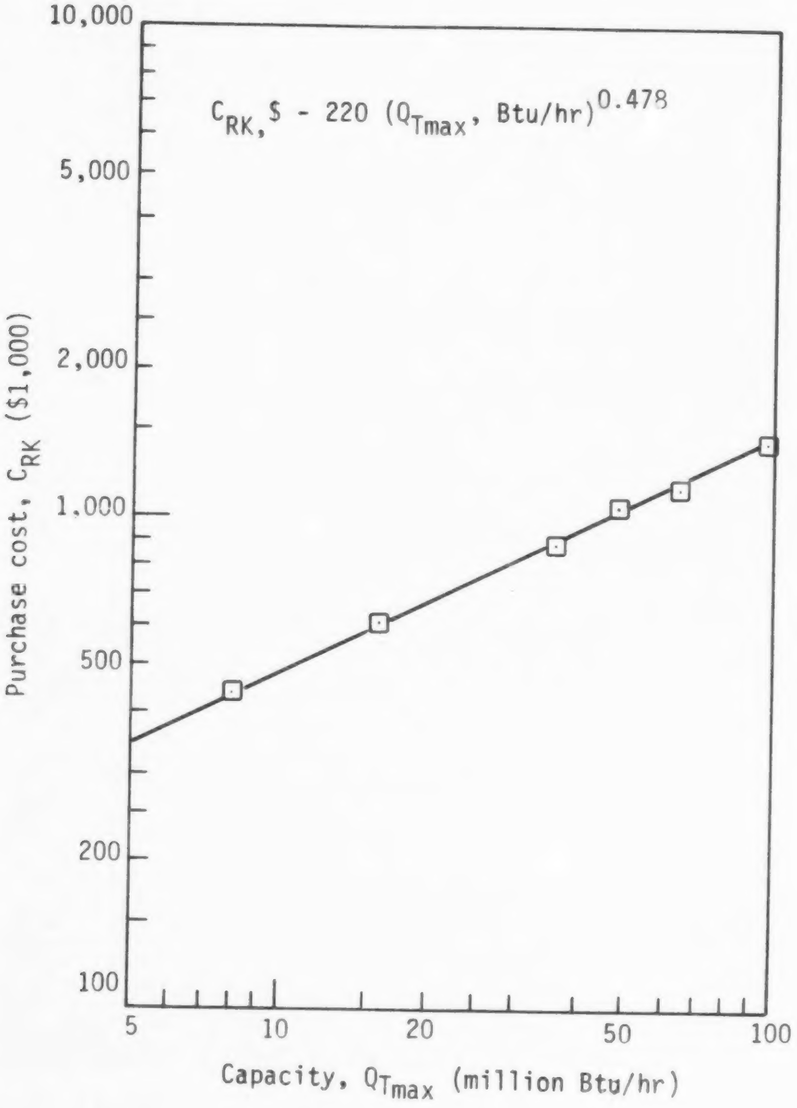


Figure 26. Purchase cost of rotary kiln incinerators (May 1982).

These systems are designed for 1,600° to 1,800°F kiln temperatures, 1,800° to 2,200°F afterburner temperatures, and approximately 2 sec residence time in the afterburner.

Purchase Cost

Based on the capacity, Q_{Tmax}, specified in Section 2, and Figure 26, the purchased cost is:

C_{RK} = $\$$__________

4.2.4.2 Waste Heat Boilers

See Section 4.2.3.2.

4.2.4.3 Scrubbing Systems

See Section 4.2.3.3. Note, from Section 3, that a venturi scrubber is almost universally required for particulate control.

4.2.4.4 Total Installed Cost for Rotary Kiln Incineration Systems

Basis

Delivery and installation cost multipliers are approximately the same for rotary kiln systems as for liquid injection incinerator systems (see Section 4.2.3.4).

Total Installed Cost

Total installed cost is given by:

$$C_{TIS} = 1.55(C_{RK} + C_{WHB} + C_{scrub})$$

= $\$$__________

4.2.5 Multiple Chamber, Hearth Incineration Systems

As for liquid injection and rotary kiln incineration systems, hearth systems include the multiple chamber combustion unit plus a waste heat boiler (optional) and scrubbing/flue gas handling system.

4.2.5.1 Multiple Chamber Hearth Incinerators

Basis

Hearth incinerator designs and costs vary from vendor to vendor. Many of these designs are not suitable for hazardous waste service because they are oriented strictly towards refuse processing. Therefore, the purchased costs for hearth incinerators shown in Figure 27 are based on designs that are capable of the high-temperature operation required.

Design features of such units include:

- Primary and secondary chambers of steel shell construction with high-temperature (approximately 3,000°F rated) refractory linings
- Ash ram and controls, quench tank, and conveyor in the larger sizes (>10 million Btu/hr)
- Ram feeder for bulk solids, including hopper, hopper cover, loading ram, hydraulic unit, and controls
- Air-atomizing waste/fuel burners in primary and/or secondary chambers (startup burners in both)
- Combustion air blower and accessories
- Complete flame safeguard and combustion control instrumentation

These systems are designed for 1,400° to 1,800°F primary chamber operation, 1,800° to 2,000°F secondary chamber operation, and 1 to 2 sec retention time in the secondary chamber, depending on capacity.

Purchase Cost

Based on the capacity, Q_{Tmax}, specified in Section 2, and Figure 27 the purchased cost is:

C_{FH} = $__________

4.2.5.2 Waste Heat Boilers

See Section 4.2.3.2.

4.2.5.3 Scrubbing Systems

See Section 4.2.3.3.

4.2.5.4 Total Installed Cost for Multiple Chamber, Hearth Incineration Systems

Basis

Same as for liquid injection and rotary kiln incineration systems.

Cost

Total installed cost is given by:

$$C_{TIS} = 1.55(C_{FH} + C_{WHB} + C_{scrub})$$

= $__________

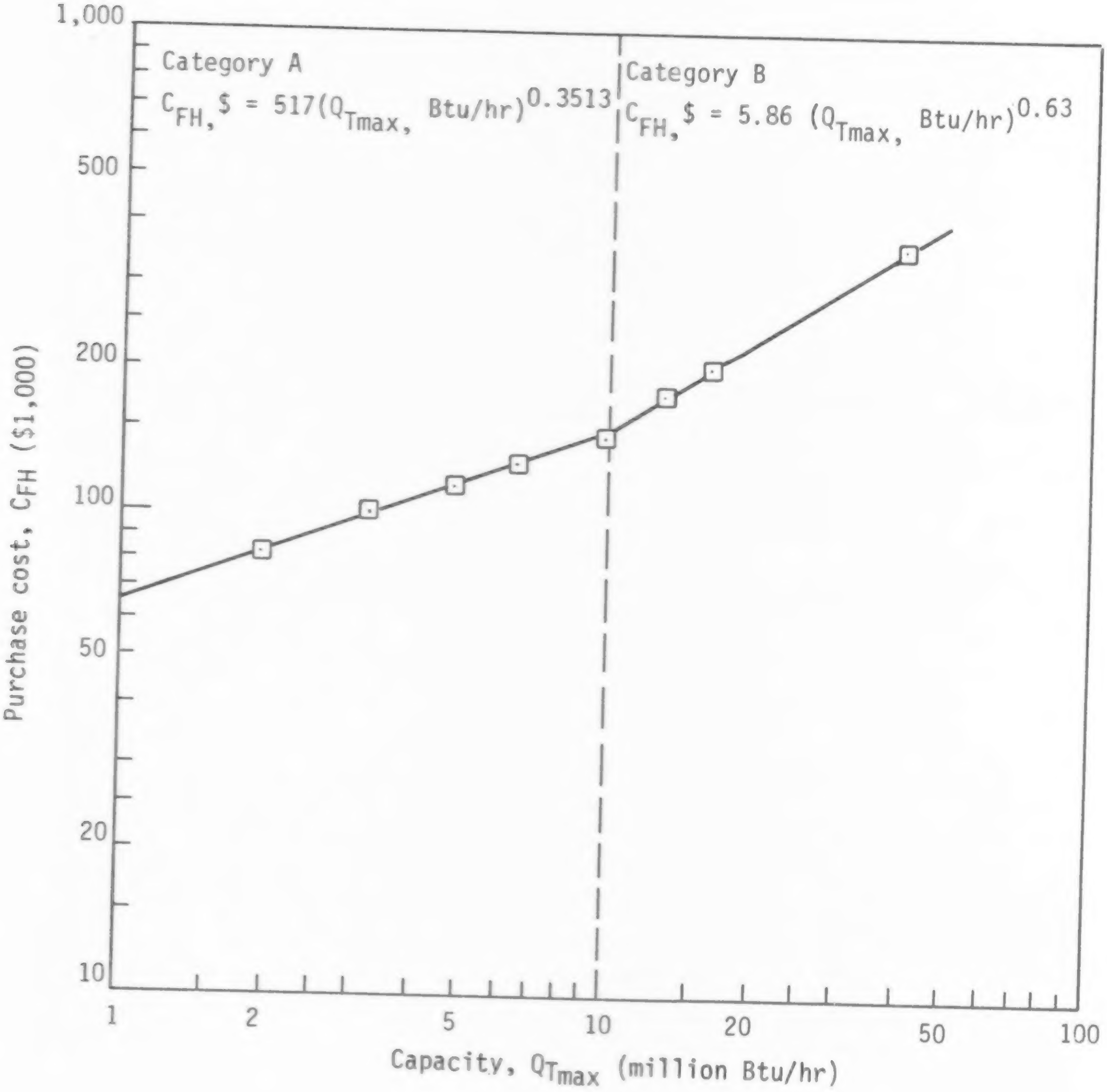


Figure 27. Purchase cost of hearth incinerators (mid 1982).

4.2.6 Summary of Direct Costs

The total direct cost (C_{TD}) is given by:

$$C_{TD} = C_{SD} + C_{tank} + C_{pump} + C_{pipe} + C_{cart} + C_{veh} + (C_{conv})_{WBS} + (C_{conv})_{WCS} + C_{comp} + (C_{bldg})_{UL} + (C_{bldg})_{WBS} + (C_{bldg})_{WCS} + (C_{bldg})_{comp} + (C_{bldg})_{CR} + C_{TIS} = \$\_\_\_\_\_\_\_\_\_\_$$

4.3 INDIRECT COSTS AND CONTINGENCY

4.3.1 Engineering Costs

Basis

Engineering costs prior to facility construction include consultant charges for feasibility studies, in-house or consultant costs for site layout and preliminary design studies, and costs for front-end storage and handling system design. These costs may range from less than 5 percent of the total direct cost for large, category C facilities, to 10 percent of the total direct cost for category A facilities, with 7.5 percent a reasonable average for category B facilities.

These estimates do not include engineering costs for incineration system design. These costs are included in the purchase prices for equipment supplied by incinerator, waste heat boiler, and air pollution control system vendors.

Cost

Based on the preceding assumptions, engineering design costs for category A facilities are estimated by:

$$C_{ED} = 0.1\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

For category B facilities:

$$C_{ED} = 0.075\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

For category C facilities:

$$C_{ED} = 0.05\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

4.3.2 Administrative Costs

Basis

Administrative costs prior to and during construction are primarily related to obtaining air pollutant discharge permits. Preparation and submission of permit applications and interfacing with federal and/or state EPA officials can require substantial engineering and administrative manhours. With the recent advent of RCRA regulations for hazardous waste incineration, it is difficult to estimate what the expenses for permitting will be in the near future. Some of the factors that can influence permitting costs are:

- Number of discrete waste streams to be handled by the facility. Dedicated incineration facilities designed to burn a small number of well-characterized process wastes represent the simplest case in terms of permit preparation and evaluation. Commercial incineration facilities represent the other extreme. Operators of commercial facilities cannot specify *a priori* the numbers of discrete waste streams that will be processed, which complicates the permitting process to a considerable degree.

- *A priori* characterization of the waste mix. Again, the permitting process is simplified when the chemical composition of the waste mix can be specified. This is usually possible for dedicated incineration facilities, designed to handle specific waste disposal problems. For commercial facilities, however, the composition of the waste mix cannot be specified *a priori*, although limitations can be set on the types of wastes accepted (e.g., no PCB's) and the elemental composition of the wastes (e.g., no more than a predetermined halogen content).

- Number and toxicity of principal organic hazardous constituents (POHC's) in the waste mix. The permit evaluation process will be more intensive if extremely toxic materials are to be burned. More extensive interfacing with EPA officials is almost certain in such cases.

- Capacity of the facility, or total volume of waste burned. Given the same level of air pollution control system sophistication, large facilities will emit larger quantities of air pollutants than smaller facilities. Thus, the larger facilities will logically demand a more intensive permit evaluation process.

- Presence of particulate-forming inorganics in the waste mix, particularly toxic metals. Volatile metallic waste constituents which vaporize in the combustion zone and later condense to form submicron particles present a very difficult particulate control problem. This problem may be of particular concern to permitting officials if the volatile metals are highly toxic, such as arsenic, mercury, or selenium. In "nonroutine" gas cleanup cases such as this, a more lengthy and costly permitting process may be anticipated.

- Conventionality and perceived adequacy of the incinerator and air pollution control system designs. Conventional incinerator and scrubber designs provided by reputable vendors with years of experience in the hazardous waste business are likely to be viewed more favorably by permitting officials than unconventional, in-house designs developed by firms with little or no hazardous waste experience.

- Availability of emissions test data for similar incineration systems burning similar waste mixes. Obviously, emissions data verifying acceptable performance is the best way to simplify the permitting process. The inherent problem with this approach lies in the definition of similarity between the proposed facility and an existing facility for which emissions data are available. To date, EPA has adopted no formal guidelines to determine a reasonable similarity between incineration processes, so the decision-making procedure is largely subjective.

- Trial burn data demonstrating that the facility in question meets local, state, and Federal performance standards. This is usually the final step necessary to obtain operating permits. However, trial burns are post-construction activities addressed in Section 4.4.3. This section deals only with permitting activities up to and during the construction period.

Obviously, the time and cost required to obtain permits to construct and operate a hazardous waste incineration facility can vary substantially. Moreover, many of the factors that can influence permitting costs are subjective and cannot be quantified within the framework of this study. The one generalization that can be made is that permitting costs will be roughly proportional to the size and complexity of the facility in question, within certain categorical size ranges. Direct costs for site development, equipment purchase, and installation are also proportional to facility size and complexity, again within the categorical size ranges established in this report. Therefore, for the budgetary costing purposes of this study, permitting costs up to and during construction are estimated as percentages of the total direct cost. The recommended percentages are 5 percent of the total direct cost for category C facilities, 7.5 percent for category B facilities, and 10 percent for category A facilities.

These estimates include allowances for (1) preparation of the necessary technical support data by in-house engineering personnel, (2) preparation of state, local, and RCRA permit forms by a senior engineering consultant, working with in-house staff, (3) time, travel, and per diem for consultant (and/or in-house personnel) interfacing with EPA officials, (4) cooperative development of a trial burn plan by consultants and in-house staff, (5) involvement of in-house administrative personnel, and

(6) all necessary clerical labor. Estimates should be realistic, and possibly conservative, for most cases except:

- Facilities planning to burn highly controversial wastes, and
- Facilities located in areas with extremely strict air pollution control regulations

In these cases, permitting costs will be highly case-specific and not amenable to treatment within the scope of this study.

It is also important to remember that hazardous waste incineration permitting under RCRA regulations is a relatively new endeavor with little historical precedent. Permitting costs are likely to be less in the long-term as more empirical data on incinerator performance become available.

Cost

Based on the preceding assumptions, administrative (permitting) costs up to and during construction for category A facilities are estimated by:

$C_{Adm} = 0.1\ (C_{TD}) = \$$__________

For category B facilities:

$C_{Adm} = 0.075\ (C_{TD}) = \$$__________

For category C facilities:

$C_{Adm} = 0.05\ (C_{TD}) = \$$__________

4.3.3 Construction Expenses and Fee

Basis

Construction costs, other than direct installation material and labor costs, include construction supervision, overhead costs, and fee.

Indirect construction expenses normally run about 10 percent of the total direct cost for facility construction. Fees range from 5 percent to 10 percent, but 7.5 percent is a reasonably representative value.

Cost

Based on these assumptions, the cost for construction expenses and fee (C_{CEF}) are given by:

$C_{CEF} = 0.175(C_{TD}) = \$$__________

4.3.4 Contingency

Basis

Contingency is commonly estimated as 10 percent of the total direct and indirect construction costs.

Cost

From this assumption, contingency cost is:

$$C_{cont} = 0.1 \left(C_{TD} + C_{ED} + C_{Adm} + C_{CEF}\right)$$

$$= \$\_\_\_\_\_\_\_\_\_\_$$

4.3.5 Summary of Indirect Costs

$$C_{TID} = C_{ED} + C_{Adm} + C_{CEF} + C_{cont} = \$\_\_\_\_\_\_\_\_\_\_$$

4.4 NONDEPRECIABLE COSTS

4.4.1 Land

Basis

Land purchase is normally considered part of the total direct cost. However, because land is not depreciable, costs for land purchase in this study are not included in the total direct cost to simplify the mathematics for nondepreciable fixed capital investment calculation.

Land purchase is only required for category C facilities. For category A and B facilities, space for the incineration system and auxiliaries is assumed to be available at the plant site.

Land costs are quite variable from location to location throughout the United States, even within metropolitan areas. Representative land costs for four major industrial areas are presented in Table 32. These estimates are for prime land zoned heavy industrial, with all utilities available at battery limits. The sources of these cost estimates are local chambers of commerce and industrial real estate firms.

Cost

Land purchase costs for category C facilities are determined from the acreage requirements shown in Figure 10, and the dollar per acre costs listed in Table 32.

$$C_{land} = (A_{land})(UC)_{land}$$

$$= \$\_\_\_\_\_\_\_\_\_\_$$

TABLE 32. REGIONAL LAND COSTS (LATE 1982)

Location	Range of costs ($1,000/acre)	Mean cost, $(UC)_{land}$ ($1,000/acre)
Chicago area	43 to 76	60
Houston area	15 to 40	27
Los Angeles area (Riverside)	130 to 152	141
Northern New Jersey	20 to 100	60

4.4.2 Startup

Basis

Startup costs include allowances for onsite time by personnel from the incineration system manufacturer(s), minor design changes, and operator training.

These costs are usually 1 to 3 percent of the total direct cost, although considerable variation is possible depending on the difficulties encountered. Recommended estimates are 1 percent of the direct cost for category C facilities, 2 percent for category B facilities, and 3 percent for category A facilities.

Cost

Based on these assumptions, startup costs for category A facilities are given by:

$$C_{start} = 0.03\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

For category B facilities:

$$C_{start} = 0.02\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

For category C facilities:

$$C_{start} = 0.01\ (C_{TD}) = \$\_\_\_\_\_\_\_\_\_\_$$

4.4.3 Trial Burns

Basis

Under current RCRA regulations, hazardous waste incineration facility owner/operators are usually required to perform a trial burn as the final step in obtaining an operating permit. As discussed in Section 4.3.2, EPA will consider emissions data provided by the owner/operator in lieu of a trial burn. For conservative cost estimating purposes, however, it is assumed in this study that a trial burn is required.

The objective of the trial burn is to demonstrate compliance with RCRA standards for destruction and removal efficiency (DRE) of any POHC's in the waste mix, particulate emission control, and HCl removal from the flue gas. Even though a variety of different wastes are burned in many incineration facilities, permitting officials may often accept a trial burn conducted under a single set of operating conditions for DRE evaluation purposes. This is based on the assumption that:

- "Normal operating conditions," and perhaps slightly higher than normal waste feedrates are used, and
- The POHC's of primary interest (based on concentration in the overall waste mix, toxicity, or public concern) are all included in the waste matrix used for testing purposes

However, two or more trial burns under different operating conditions may be required for large facilities proposing to burn complex mixtures of waste containing numerous POHC's under different sets of operating conditions. The exact requirements must be negotiated on a case-by-case basis.

A single trial burn usually consists of triplicate runs under the prespecified waste firing conditions, plus a baseline run in which only startup fuel is burned. Sampling techniques used for each run include:

- Modified EPA Method 5 (with XAD resin trap) for particulate and high-boiling ($>C_6$) organics in the stack gas
- Volatile Organic Sampling Train (VOST) for C_1 to C_6 organics in the stack gas. EPA is now conducting a priority development program in this area.
- Mini-impinger train for Cl/Cl_2 collection
- Continuous monitors for O_2, CO, CO_2, total hydrocarbons, NO_x, and SO_2
- Grab samples of each waste stream and liquid/solid process effluent (e.g., bottom ash, scrubber blowdown)

All organics analyses are performed using appropriate GC, GC/ECD, or GC/MS techniques.

The costs for trial burns include labor and materials for the sampling and analysis activities, travel and per diem for the sampling team (unless a local contractor is used). These costs can vary substantially depending on the number and complexity of the tests required. In cases where system complexity and the number of POHC's are minimal, typical costs range from $50,000 to $100,000. It is possible for these costs to be 25 to 50 percent higher when large numbers of POHC destruction efficiencies need to be evaluated or for large, complex incineration systems.

Based on these considerations, reasonably conservative cost estimates for trial burns are $75,000 for category A facilities, $100,000 for category B facilities, and $150,000 for category C facilities. These cost estimates only cover trial burn performance; other permitting costs are estimated in Section 4.2.3.

Costs

Based on the preceding discussion, trial burn costs for category A facilities are estimated to be:

$$C_{TB} = \$75,000$$

For category B facilities:

$$C_{TB} = \$100,000$$

For category C facilities:

$$C_{TB} = \$150,000$$

4.4.4 Working Capital

Basis

For hazardous waste incineration facilities, working capital includes the onsite fuel oil inventory, caustic soda solution inventory, and maintenance materials (spare parts, etc.).

Fuel oil and caustic soda solution inventories are taken as the total storage tank capacities. Dollars per gallon costs for fuel oil, $(UC)_{FO}$, vary on a regional basis. Costs for four areas around the country are given in Table 33, Section 5.3.1, under operating cost estimation.

Caustic soda solution has a density of 11 lb/gal, and costs approximately $0.07/lb or $0.77/gal.

Maintenance materials account for approximately one-half of the total maintenance cost, and 3-month inventories are maintained. Thus, the working capital requirement for maintenance materials is roughly one-eighth of the annual maintenance cost (C_M) estimated in Section 5.4.2.

Cost

Based on these assumptions, the cost for working capital is given by:

$$C_{WC} = (5{,}000\ N_{FO5} + 10{,}000\ N_{FO10} + 20{,}000\ N_{FO20})(UC)_{FO}$$
$$+\ 0.77(5{,}000\ N_{CSS5} + 10{,}000\ N_{CSS10} + 20{,}000 N_{CSS20})$$
$$+\ 0.125\ C_M$$
$$= \$\underline{\hspace{3cm}}$$

4.4.5 Summary of Nondepreciable Costs

$$C_{TNDC} = C_{land} + C_{start} + C_{TB} + C_{WC}$$
$$= \$\underline{\hspace{3cm}}$$

4.5 FIXED CAPITAL AND TOTAL CAPITAL INVESTMENT SUMMARIES

As explained at the beginning of Section 4, depreciable fixed capital investment is the sum of the direct and indirect costs:

$$DFCI = C_{TD} + C_{TID} = \$\underline{\hspace{3cm}}$$

And the total capital investment is:

$$TCI = DFCI + C_{TNDC} = \$\underline{\hspace{3cm}}$$

SECTION 5

ANNUAL COST ESTIMATION

5.1 OVERVIEW

The annual cost for incinerator facility operation is the sum of the variable operating costs, semivariable O&M costs, and fixed charges to capital, minus any energy recovery credit. Variable operating cost elements for most hazardous waste incineration facilities include fuel (natural gas, fuel oil, propane, diesel oil, etc.), electric power, water, acid-gas neutralization chemicals such as caustic soda, liquid nitrogen, and residue disposal. These are referred to as variable operating cost elements because they can usually be expressed in terms of dollars per ton (pounds, gallons, etc.) of waste disposed. In other words, the annual variable operating cost total is more or less proportional to annual facility utilization. This would seem to indicate that annual facility utilization, or onstream time per year, is unimportant in estimating O&M costs for hazardous waste incineration in dollars per ton or the equivalent. In practice, however, the opposite is often true because variable operating costs can constitute less than half of the total annual cost of facility operation.

The other costs that impact incinerator operation are fixed charges to capital -- amortization, insurance, and taxes -- and semivariable costs such as operating labor and supervision, clerical/administrative labor, maintenance materials and labor, and waste analyses. These costs are not directly related to annual facility utilization. In fact, they are usually related to facility size and capacity, or they are relatively constant for all facilities.

Therefore, the following approach is recommended to develop unit cost estimates for hazardous waste incineration from the engineering calculations presented in Section 3.

- Develop guidelines for facility operating schedule and annual percentage utilization, based on the input data specified in Section 2

- Use these guidelines in conjunction with unit cost data for utilities and raw materials, as well as the utility and raw material consumption rates calculated in Section 3, to estimate the total annual cost for each variable operating cost element

- Estimate annual, semivariable costs for labor, maintenance, and analysis independent of the specified facility operating schedule

- Estimate fixed costs based on the estimated depreciable fixed capital investment from Section 4

- Estimate fuel conservation credits for waste heat boiler operation from the rate-based calculations in Section 3 and the specified annual utilization percentage

- Summarize these annual costs and credits and divide by the total quantity of waste processed annually to derive a unit disposal cost

Steps 1 through 5 of this approach are addressed in the following subsections, and the final step is addressed in Section 6.

5.2 OPERATING SCHEDULES AND ANNUAL FACILITY UTILIZATION

Weekly operating schedules for hazardous waste incineration facilities are usually determined by the type of business in which the owner and/or operator is employed. Institutions such as universities, commercial business operations, public or private laboratories, etc., often do not operate on a 24-hr/day, 7-day/week basis. Therefore, wastes are not generated continuously. Even in institutions such as hospitals that do operate around-the-clock, wastes are usually dispatched to the disposal facility only one shift per day, and operating personnel are reduced to a minimum on other shifts to minimize expenses.

Hazardous waste incinerators owned and operated by these types of institutions are primarily category A facilities, as defined in Section 2, with capacities in the 1 to 10 million Btu/hr range. Solid waste incinerators of this size almost never justify the costs for automatic waste feeding and ash removal, so operation is labor intensive and daily shutdowns for ash removal are required, unless extremely low ash content wastes are burned. This usually dictates a 5-day/week, 8-hr/day operating schedule. Operating schedules of 6 days/week, 16 hr/day may also be employed, but the more conservative one-shift schedule is recommended for cost estimating purposes. A one-shift schedule assumption is also recommended for category A liquid waste incinerators, even though these units are capable of continuous operation. The rationale behind this assumption is that firms purchasing liquid injection units in this size range do so for one of two reasons in many cases: (1) it is the smallest capacity unit commercially available, or (2) business expansion is anticipated. In either case, it can be profitable to purchase the oversized unit when considering current regulatory standards for offsite disposal of liquid wastes.

Larger incinerators normally operate on a 7-day/week, 24-hr/day schedule. Incineration facilities with capacities in the 10 to 50 million Btu/hr range (category B) are usually owned and operated by chemical plants, refineries, or other large industrial operations for captive waste disposal.

These plants normally employ four shifts per week, and generate wastes continuously or in frequent, though discrete, batches. Therefore, 24-hr/day, 7-day/week operation of an incineration facility is in line with typical business practice. It is also more economical for these owners and/or operators because frequent startup costs and the indirect downtime costs for intermittent operation are avoided. In addition, over capacity and the higher associated capital expenditure is minimized. The cost savings associated with continous operation of >10 million Btu/hr incineration facililties normally justify the increased capital requirements for automatic waste feeding equipment, ash removal equipment, and sophisticated control instrumentation. This is particularly true if heat in the incinerator exit gas can be recovered to generate process steam and simultaneously reduce fuel consumption in the plant boiler complex.

Continuous operation of large category C (50 to 100 million Btu/hr) incineration facilities is not only preferred, but almost mandatory for economical performance. These facilities are often owned by commercial waste disposal firms whose profits depend on continuous throughput. Other incinerators in this size range are usually corporate central or semiprivate facilities receiving large quantities of wastes from a limited number of manufacturing plants. It would be unprofitable for owners and/or operators of these types of facilities to design for anything less than a 24-hr/day, 7-day/week operation because these owners almost always have an interest in the manufacturing operations, whose profits are affected by the efficiency and costs of waste disposal.

Although the goal of most category B and C incineration facility owners is 24-hr/day, 7-day/week operation, 100 percent annual onstream time is virtually impossible to achieve. The reasons for this include:

- Processes generating hazardous wastes seldom achieve better than 330 stream-day per year operation, or 90 percent onstream time. This can require shutdown of private, semiprivate, or corporate central incinerator facilities unless a substantial waste backlog is maintained.

- Although these classes of incinerators are designed for 24-hr/day operation, they may also be somewhat oversized for the current, annual waste disposal requirement. In these situations, burning campaigns of 2 weeks to 1 month duration are normally scheduled, with equivalent or lesser downtimes planned for the interim periods. Wastes may be continuously accumulated in storage during these periods, or accumulated all at once from batch operations.

- Category C commercial waste disposal facilities are also susceptible to long downtime periods from lack of business. Some of these facilities are equipped with weeks of storage capacity, so long burn campaigns can be conducted without daily waste deliveries. Eventually, however, shutdown is required if waste deliveries do not meet the normal incinerator feed requirements.

- In addition, all incineration facilities are subject to scheduled and/or unscheduled downtime for maintenance, regardless of waste availability

Considering each of these factors, the probable range of annual utilization percentages for category B and C facilities is 50 to 90 percent. The high end of the range represents near optimum conditions, while the low end of the range reflects extensive maintenance downtime or low waste availability. User discretion is needed to select an appropriate utilization factor, $0.50<UF<0.90$, for the calculations presented in the following sections. The selected value should be entered in Section 2.

For category A facilities, the theoretical, annual utilization percentage is only 24 percent due to the assumption of 5-day/week, 8-hr/day operation. The recommended utilization factor (UF) for these facilities is 0.22. This allows a continuous, 4-week downtime period each year for heavy maintenance in addition to the daily downtimes. However, a different utilization factor (e.g., one based on continuous operation) may be entered in Section 2.

5.3 VARIBLE COSTS

5.3.1 Fuel

The fuel requirements for facility operation include:

- No. 2 fuel oil for supplemental heating, F_{FO}; and startup, $(M_{FO})_{start}$
- Natural gas for low-fire flame stabilization (q_{NG})
- Propane for lift truck operation

TABLE 33. UNIT COSTS FOR FUEL OIL AND NATURAL GAS (JANUARY 1983) (REFERENCES 8, 9, 10)

Region	Unit cost for no. 2 fuel oil, $(UC)_{FO}$ (\$/gal)	Unit cost for natural gas, $(UC)_{NG}$ (\$/1,000 ft^3)
Chicago area	0.94	4.85
Houston area	0.92	4.52
Los Angeles area	0.94	4.04
Northern New Jersey	0.94	5.70

Approximate industrial user costs for no. 2 fuel oil and natural gas, by region, are presented in Table 33.

5.3.1.1 Fuel Oil for Supplemental Heating

Basis

Fuel oil density is 53 lb/gal, and the total number of hours per year at 100 percent utilization is 8,760.

Annual Cost

$C_{F1} = 165(F_{FO})\ (UF)(UC)_{FO} = \$\_\_\_\_\_\_\_\_\_/\text{year}$

5.3.1.2 Fuel Oil for Startup

Basis

For category A facilities operating 8 hr/day, 5 days/week, 48 weeks/year, the number of startups is:

$N_{start} = 5 \times 48 = 240$ startups/year

For category B and C facilities, typical burn campaigns last 2 to 4 weeks. Assuming 2-week burn campaigns:

$N_{start} = 26\ (UF) =$ _____ startups/year

For 4-week burn campaigns:

$N_{start} = 13\ (UF) =$ _____ startups/year

User discretion is needed to select an appropriate N_{start} value. The selected value should be entered in Section 2.

Annual Cost

$C_{F2} = 0.139\ (M_{FO})_{start}\ (N_{start})\ (UC)_{FO} = \$\_\_\_\_\_\_\_\_\_/\text{year}$

5.3.1.3 Natural Gas

Basis

Natural gas heating value is 1,000 Btu/ft^3

Annual Cost

$C_{F3} = 8.76_{q_{NG}}\ (UF)(UC)_{NG} = \$\_\_\_\_\_\_\_\_\_/\text{year}$

5.3.1.4 Propane

Basis

Propane costs for lift truck operation are approximately \$0.75/hr

Annual Cost

$C_{F4} = 6{,}570\ \theta_{veh}\ (UF) =$ \$________/year

5.3.1.5 Summary of Fuel Costs

$C_F = C_{F1} + C_{F2} + C_{F3} + C_{F4} =$ \$________/year

5.3.2 Power

Basis

Typical electric power costs for industrial users, by region, are presented in Table 34. Noninterruptible supply is assumed in all cases.

Total power demand is given by:

$$P = [(P_{pump})_{WCL} + (P_{pump})_{WNL} + (P_{pump})_{trans} + (P_{pump})_{WPS} + P_{heat} + (P_{conv})_{WBS} + (P_{feed})_{WBS} + (P_{conv})_{WCS} + P_{drive} + (P_{pump})_{FO} + P_{comp} + P_{bl} + (P_{pump})_{AW} + (P_{conv})_{ash} + (P_{pump})_{QW} + (P_{pump})_{VSW} + (P_{pump})_{CSS} + (P_{pump})_{AbW} + (P_{pump})_{SMW} + P_{fan} + P_{Ag}]\ (0.7457\ kw/hp) = \underline{\hspace{4cm}}\ kw$$

Annual Cost

$C_P = 8{,}760\ (P)\ (UF)(UC)_P =$ \$________/year

5.3.3 Water

Basis

Typical water costs for industrial users, by region, are presented in Table 35. These costs were obtained from municipal suppliers. Lower costs may be anticipated if private process water sources are available. In catebory B incineration facilities owned and operated by large production companies, water costs may be essentially zero if wastewater treatment plant

TABLE 34. UNIT COST FOR ELECTRIC POWER (JANUARY 1983)(REFERENCES 8, 9, 10)

Region	Unit power cost, $(UC)_p$ ($/kwh)
Chicago area	0.064
Houston area	0.056
Los Angeles area	0.065
Northern New Jersey	0.074

TABLE 35. UNIT COSTS FOR WATER (LATE 1982)[a]

Region	Unit water cost, $(UC)_{water}$ ($/1,000 gal)
Chicago area	0.71
Houston area	0.25
Los Angeles area (Riverside)	0.47
Northern New Jersey (Newark)	0.79

[a] Baseline rates for large volume industrial users.

effluent can be recycled as scrubber makeup water. For conservative cost estimating purposes, however, the values presented in Table 35 are recommended.

Annual Cost

$$C_{water} = 525.6\ (q_{AW} + q_{SMW})(UF)(UC)_{water} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

5.3.4 Chemicals

The main chemical requirements are caustic soda solution for acid gas scrubbing and liquid nitrogen for tank blanketing.

5.3.4.1 Caustic Soda Solution

Basis

Costs for 50 percent caustic soda solution are approximately \$140/ton, or \$0.07/lb, in mid to late 1982 dollars. This estimate is based on a manufacturer quotation.

Annual Cost

$C_{CSS} = 613.2\ F_{CSS}\ (UF) = \$\_\_\_\_\_\_\_\_/\text{year}$

5.3.4.2 Liquid Nitrogen

Basis

In category A facilities, liquid nitrogen requirements for tank blanketing can usually be provided by ≤ 2 cylinders per day. In larger facilities, however, a pressure tank for bulk liquid nitrogen storage is usually a more economical alternative. These tanks are normally rented from the liquid nitrogen supplier. Therefore, liquid nitrogen costs for category B and C facilities include storage tank rental charges. For category A facilities, a \$2.75 rental charge is included for each 280-ft^3 cylinder.

Table 36 presents unit costs for liquid nitrogen, as well as annual storage tank rental charges for category B and C facilities. These costs are based on supplier quotations.

Annual Cost

$C_{LN} = 87.6\ q_{LN}\ (UF)(UC)_{LN} + (C_{tank})_{LN} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$

TABLE 36. LIQUID NITROGEN COSTS (MID 1982)

Facility category	Unit cost for liquid nitrogen $(UC)_{LN}$ (\$/100 ft^3)	Annual storage tank rental $(C_{tank})_{LN}$ (\$)
A	6.34	0
B	1.06	2,400
C	0.68	3,800

5.3.4.3 Summary of Chemical Costs

$$C_{chem} = C_{CSS} + C_{LN} = \$\_\_\_\_\_\_\_\_/\text{year}$$

5.3.5 Residue Disposal

Total residue disposal costs include the costs for ash landfilling and wastewater (scrubber blowdown) disposition.

5.3.5.1 Ash Disposal

Basis

For category A solid waste incinerators, dry ash removal and handling are assumed. For larger facilities, water quenching is assumed followed by conveyor removal as a 50:50 sludge mixture of water and ash.

Unit disposal costs for landfilling these residues depend on location, whether the material is wet or dry, and, most important, whether or not toxic metals are present. If toxic metals are present, secure landfilling is required. Some typical unit costs are shown in Table 37. These estimates are based on discussions with landfill owner/operators.

Annual Cost

For category A rotary kilns (dry ash):

$$C_{ash} = 6{,}570\ (F_{ash})_{WS}\ (UF)(UC)_{ash} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

TABLE 37. UNIT DISPOSAL COSTS FOR LANDFILLING (MID TO LATE 1982)

	$(UC)_{ash}$ (\$/lb)			
	Sanitary landfill		Secure landfill	
Region	Wet	Dry	Wet	Dry
Chicago area	0.007	0.007	0.022	0.022
Houston area	0.004	0.002	0.035	0.030
Los Angeles area	0.010	0.010	0.014	0.012
Northern New Jersey	0.001	0.001	0.048	0.048

For category A hearth incinerators (dry ash):

$$C_{ash} = 8{,}322\ (F_{ash})_{WS}\ (UF)(UC)_{ash} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

For larger kilns and the more actively stoked hearth designs (ash sludge):

$$C_{ash} = 13{,}140\ (F_{ash})_{WS}\ (UF)(UC)_{ash} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

And for the less actively stoked category B hearth incinerators (ash sludge):

$$C_{ash} = 16{,}644\ (F_{ash})_{WS}\ (UF)(UC)_{ash} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

5.3.5.2 Wastewater Disposal

Basis

Typical wastewater acceptance charges, or sewer charges, are presented by region in Table 38. The costs are based on discussions with municipal sewer district personnel.

In practice, the larger category B and C facilities often discharge wastewater to onsite or corporate central treatment plants, where the costs may well be negligible when the scrubber blowdown rate is compared to the plant-wide wastewater flow. However, the unit costs listed in Table 38 are recommended for conservative estimating purposes.

Annual Cost

$$C_{WW} = 525.6\ q_{BdW}\ (UF)(UC)_{WW} = \$\_\_\_\_\_\_\_\_\_\_/\text{year}$$

TABLE 38. SEWER CHARGES (MID TO LATE 1982)

Region	Sewer charge, $(UC)_{WW}$ ($/1,000 gal)
Chicago area	0.32
Houston area	1.29
Los Angeles area (Riverside)	0.51
Northern New Jersey (Newark)	1.40

5.3.5.3 Summary of Residue Disposal Costs

$C_{res} = C_{ash} + C_{WW} = \$$_________/year

5.3.6 Summary of Annual Variable Costs

$C_{AV} = C_F + C_P + C_{water} + C_{chem} + C_{res} = \$$_________/year

5.4 SEMIVARIABLE COSTS

5.4.1 Operating Labor and Supervision

Basis

Operating personnel for incineration facilities are broken into six categories: process operators, lift truck operators, yard laborers, clerical personnel, engineering supervisors, and administrators.

Typical wages and salaries for these personnel categories, by region, are shown in Table 39. Estimates of the number of each of these types of personnel needed in various incineration facilities are presented in Tables 40 through 42. In addition, a 40 percent burden is attached to cover employee benefits. For hourly personnel, the annual pay period is 2,080 hours.

TABLE 39. LABOR COSTS (MID TO LATE 1982)

Region	Process operator ($/hr)	Forklift operator ($/hr)	Yard laborer ($/hr)	Clerical ($/hr)	Engineering supervisor ($/year)	Administrator ($/yr)
Chicago area	9.80	7.64	6.70	6.28	32,000	48,000
Houston area	11.00	8.50	5.00	5.00	40,000	60,000
Los Angeles area	9.30	7.27	7.80	7.45	36,000	53,000
Northern New Jersey	8.90	6.55	5.37	6.13	29,000	48,000

TABLE 40. ESTIMATED LABOR REQUIREMENTS FOR CATEGORY A FACILITIES

	Liquid wastes only			Liquid and solid wastes		
Labor category	Number per shift	Number of shifts	Total number of personnel	Number per shift	Number of shifts	Total number of personnel
Process operator	1	1	1	1	1	1
Forklift operator	0	0	0	1	1	1
Yard laborer	0	0	0	1	1	1
Engineering supervisor	0.25	1	0.25	0.25	1	0.25

TABLE 41. ESTIMATED LABOR REQUIREMENTS FOR CATEGORY B FACILITIES

	Liquid wastes only			Liquid and solid wastes		
Labor category	Number per shift	Number of shifts	Total number of personnel	Number per shift	Number of shifts	Total number of personnel
Process operator	1	4	4	1	4	4
Forklift operator	0	0	0	1	4	4
Yard laborer	0	0	0	1	4	4
Engineering supervisor	0.5	1	0.5	0.5	1	0.5

TABLE 42. ESTIMATED LABOR REQURIEMENTS FOR CATEGORY C FACILITIES

	Liquid wastes only			Liquid and solid wastes		
Labor category	Number per shift	Number of shifts	Total number of personnel	Number per shift	Number of shifts	Total number of personnel
Process operator	3 2	1 3	-- 9	3 2	1 3	-- 9
Forklift operator	0	0	0	1	4	4
Yard laborer	0	0	0	1	4	4
Clerical	0.5	1	0.5	0.5	1	0.5
Engineering supervisor	1	1	1	1	1	1
Administrator	1	1	1	1	1	1

Annual Cost

C_L = 2,912 [(total no. of process operators) (wage, \$/hr)

+ (total no. of lift truck operators) (wage, \$/hr)

+ (total no. of laborers) (wage, \$/hr)

+ (total no. of clerical workers) (wage, \$/hr)]

+ 1.4 [(total no. of engineering supervisors) (salary, \$/year)

+ (total no. of administrators) (salary, \$/year)]

= \$__________/year.

5.4.2 Maintenance

Basis

Of all the annual costs associated with incinerator facility operation, maintenance costs are the most difficult to estimate. Annual costs for maintenance materials and labor cannot be predicted as functions of a few simple waste and facility design characteristics because a myriad of site-specific factors can dramatically affect maintenance requirements. For example, the presence of certain trace elements at concentrations in the 100 ppm range can lead to accelerated refractory degradation and/or excessive waste heat boiler fouling, particularly if temperature or excess air are poorly controlled. Small cracks in the quench or absorption column lining can cause accelerated shell corrosion and require premature replacement of the unit. Pumping system maintenance costs are related to a number of site-specific factors such as pump design, flowrate and pressure, the solids content of the liquid, particle size, and the abrasiveness of the solids. Moreover, the experience and competence of the operating personnel play major roles in determining maintenance costs.

Based on these considerations, the most feasible approach to annual maintenance cost estimation for the purpose of this study is the budget estimate approach, whereby maintenance costs are predicted as a flat percentage of the depreciable fixed capital investment for a given facility. Thus, higher maintenance costs are predicted for larger capacity facilities incorporating more unit operations and facilities designed for more severe operating conditions.

The percentages of depreciable fixed capital investment (DFCI) recommended for annual maintenance cost estimation are 5 percent for liquid injection incinerator systems, 7 percent for multiple-chamber, hearth-type incinerator systems, and 10 percent for rotary kiln systems. These are considered reasonable estimates of average annual maintenance costs over the depreciable lives of the facilities.

In many industrial operations, annual maintenance costs are reduced if the plant is operated at substantially less than 100 percent utilization. This is not necesarily the case for incineration facilities, however, because increased downtime usually means more frequent startups and thermal cycling, which reduces refractory life. If extended downtime does not translate into more frequent cycling, however, the following adjustment factors are recommended:

- 15 percent reduction in maintenance cost for 50 to 75 percent annual utilization
- 25 percent reduction in maintenance cost for 50 percent or less annual utilization

Annual cost

C_M = 0.05 (DFCI) for liquid injection systems = \$__________/year

C_M = 0.07 (DFCI) for hearth-type systems = \$__________/year

C_M = 0.1 (DFCI) for rotary kiln systems = \$__________/year

If maintenance cost adjustment for reduced utilization is deemed appropriate, the appropriate multipliers are 0.85 for 50 to 75 percent utilization and 0.75 for $\leq$50 percent utilization.

5.4.3 Waste Analyses

Basis

High-volume waste analyses are required only in category C facilities which receive a large number of wastes from different sources. Category A and B facilities burn 100 percent captive wastes, the compositions of which should be relatively well known to the operator.

Waste analysis costs are very largely labor oriented. In category C facilities, one laboratory technician experienced in wet chemical methods as well as instrument analysis (e.g., infrared (IR) spectrometry) is needed one shift per day, 5 days/week. His responsibilities are to analyze waste samples from prospective customers and to run quick verification scans on incoming shipments.

Hourly wages are \$11.00/hr, plus a 40 percent burdening factor to cover benefits.

Annual pay period is 2,080 hours.

Annual Cost

C_{WA} = \$32,000/year

5.4.4 Summary of Annual Semivariable Costs

$C_{ASV} = C_L + C_M + C_{WA}$ = \$_________/year

5.5 FIXED COSTS

5.1.1 Annualized Capital Cost

Basis

Because incineration is a capital-intensive waste disposal technology, the overall O&M cost must include an annualized capital investment cost in some form or another. This annualized capital cost depends on the depreciation formula employed, period of time over which the investment is depreciated, source of funding for facility construction, and the interest rate or time value of money used for investment purposes. On the other side of the ledger, an in-depth economic analysis would also consider investment tax credits, (potential) credits for investment in energy recovery, the anticipated rate of inflation over the life of the facility, and income tax adjustments for facility operation. This type of economic evaluation is not within the scope of the present study.

Therefore, a generalized capital recovery factor of 10 percent per year is assumed for the purposes of this study. This is equivalent to simple 10-year, straight-line depreciation. If information is available on the financial structure and accounting practices of the owner/operator's organization, the user may choose to apply a more in-depth estimating technique.

Annual Cost

C_{Dep} = 0.1 (DFCI) = $____________/year

5.5.2 Insurance and Taxes

Basis

Depending on the exact location of the facility, insurance and taxes combined should be 3 to 5 percent of the fixed capital investment on a yearly basis. A median value of 4 percent is recommended.

Annual Cost

$C_{I/T}$ = 0.04 (DFCI) = $__________/year

5.5.3 Summary of Annual Fixed Costs

$C_{AF} = C_{Dep} + C_{I/T}$ = $_________/year

5.6 ENERGY RECOVERY CREDIT

Basis

Annual credits for energy recovery are based on the fuel savings calculated in Section 3 and the regional costs for fuel oil listed in Section 5.3.1.

Annual Credit

$C_{ER} = 165\ (F_{FO})_{WHB}\ (UF)(UC)_{FO}$ = \$__________/year

5.7 ANNUAL COST SUMMARY

The net annual cost for facility operation is given by,

$C_{NA} = C_{AV} + C_{ASV} + C_{AF} - C_{ER}$ = \$__________/year

SECTION 6

UNIT DISPOSAL COST CALCULATION

Unit disposal cost is determined by combining the net annual cost (C_{NA}) and the total quantity of waste disposed annually. The quantity of waste disposed annually is given by,

$$M_W = 4.38\ (F_{WCL} + F_{WNL} + F_{WPS} + F_{WBS} + F_{WCS})\ (UF) = \underline{\hspace{6em}}\ \text{ton/year}$$

Unit disposal cost is then given by,

$$C_{UD} = \frac{C_{NA}}{M_W} = \$\underline{\hspace{5em}}\ /\text{ton} \div 2{,}000\ \text{lb/ton} = \underline{\hspace{7em}}/\text{lb}$$

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